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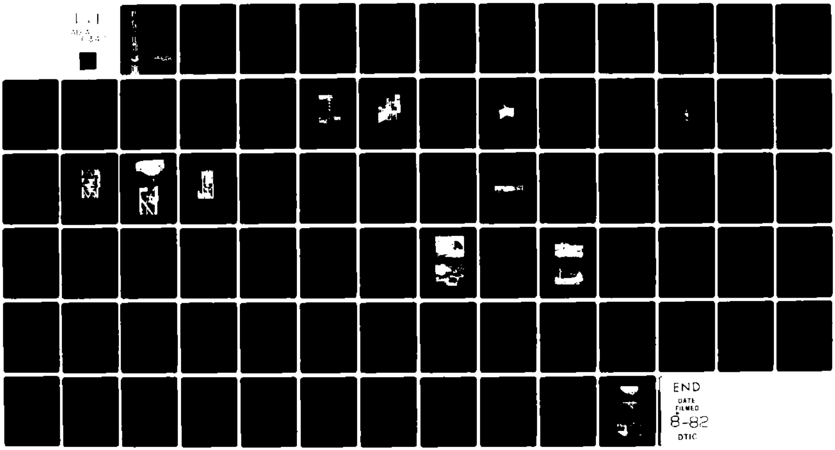

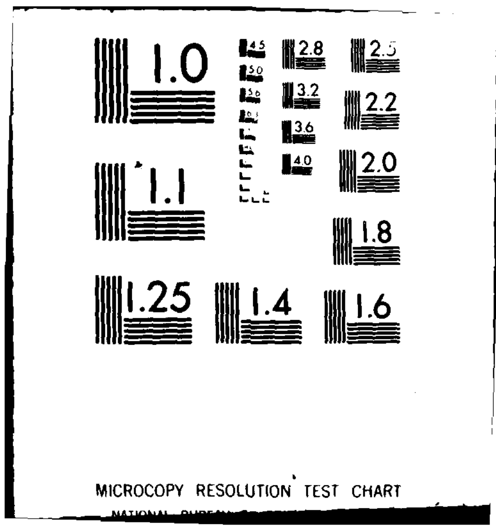
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ESL-TR-80-48

UNITED STATES AIR FORCE ACADEMY (USAFA) VERTICAL AXIS WIND TURBINE

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UNITED STATES AIR FORCE ACADEMY, CO 80840

SEPTEMBER 1980

FINAL REPORT
MAY 1977 - SEPTEMBER 1980

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This report describes the design, fabrication, installation and testing of a small variable-speed vertical axis wind turbine (VAWT). This VAWT is unique in its installation using hand tools; unconventional and simple support system; and variable speed operation under microprocessor control. Initial testing confirmed that the turbine can be controlled by commanded alternator field modulation. Further studies will be directed toward determination of an optimum control algorithm.

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PREFACE

This report was prepared by members of the Department of Engineering Mechanics (DFEM) and Civil Engineering (DFCE), United States Air Force Academy, Colorado, for the Air Force Engineering and Services Center (AFESC) under work unit 2103 8007. This work was accomplished during the period May 1977 to September 1980. Prior to 15 March 1979, this work was accomplished for the Civil and Environmental Engineering Development Office (CEEDO) which became the Engineering and Services Laboratory of the Air Force Engineering Services Center. Captain Arthur R. Fisher was the Principal Investigator for the first six months and Lt Colonel Thomas E. Kullgren for the remainder of this project. Associate Investigators during the course of this work were Lt Colonel Dennis W. Wiedmeier, Major Thomas C. Finley, Major Gary E. Brown, Captain John T. Tinsley, and Captain Joel E. Benson. Research Assistants included 2nd Lieutenant Louis S. Fikar, Michael G. Padgett, Regis T. Hancock, Scott C. Adams, and Deacon Wingers. Cadets (now 2nd Lieutenants) Michael P. Foster, Timothy J. Parker, and Penny R. Nixon contributed several designs used in the final turbine configuration. The initial Project Officer responsible for development of this work unit was First Lieutenant Michael R. Mantz of the Engineering and Services Laboratory (AFESC/RD).

The active support of the 7625th Civil Engineering Squadron, the Department of Instructional Technology, the Civil Engineering, Engineering Mechanics and Materials Laboratory, Robert B. Mann of the Department of Electrical Engineering and Mrs. Walter Bauer (DFEM) is also acknowledged.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Services (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This TR has been reviewed and is approved for publication.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONCLUDED)

LIST OF FIGURES

LIST OF FIGURES (CONCLUDED)

LIST OF TABLES

SECTION I

INTRODUCTION

1. SCOPE OF REPORT

This technical report describes the design, fabrication and initial testing of a small vertical axis wind turbine (VAWT) at the United States Air Force Academy (USAFA) during the period May 1977 to September 1980. Funding for this project was provided by the Air Force Civil and Environmental Engineering Development Organization (CEEDO), Air Force Systems Command, which later became the Engineering and Services Laboratory, Air Force Engineering and Services Center, Tyndall AFB, Florida.

The wind turbine effort is one of two tasks under the USAFA Wind Energy Conversion System Project. The other task is that of completing a wind site survey of the 18,000-acre USAFA installation and the development of a methodology to survey other installations. This latter task will not be described here but will appear as a technical report under AFESC work unit 21038011.

2. PROJECT MOTIVATION

Windmills have been producing useful energy from the beginning of recorded history. However, not until the decades of 1920 to 1960 were modern wind turbines developed and fabricated. The United States, the Soviet Union, Denmark, Great Britian, and Germany all had some experience during this period with electrical power producing machines rated from 100 to 1000 kilowatts, considered by most standards to be large wind turbines. In spite of these generally successful experiences, interest in wind turbines declined into the early 1970's because:

a. Energy derived from fossil fuels was abundant and cheap,

b. Nuclear energy was promised to be cheap, and

c. The wind is variable and there were no suitable energy storage methods available to make wind derived energy more reliable (Reference 1).

It is now evident that fossil fuels are neither abundant not cheap. Reliable estimates predict the possibility of total depletion in oil supplies early in the 21st century even with new discoveries and lower growth in demand. The Arab oil embargo of 1973 dramatically emphasized

creeping inflation which quadrupled oil prices from 1950 levels (Reference 2). The promise of inexpensive electricity from nuclear power plants was found to be difficult if not impossible to keep. Costs of $300 - $400 per installed kilowatt of nuclear based power are nearly double the costs of earlier large wind turbines which did not have the benefit of modern design technology. Although safety questions will not be addressed here, public rejection of nuclear power plants is also a real possibility. Modern technology has provided the means to solve the wind energy storage problem.

It seems that many of the barriers to the consideration of wind as a viable energy source have been eliminated, yet serious questions regarding the extraction of this energy still remain. Nevertheless, direction from the highest levels of government clearly indicate a need to investigate the potential for wind power.

The President of the United States issued the National Energy Plan on 29 April 1977. This document stated three energy objectives:

a. As an immediate objective that will become even more important in the future, to reduce dependence on foreign oil and vulnerability to supply interruptions.

b. In the medium term, to keep United States imports sufficiently low to weather the period when world oil production approaches its capacity limitation.

c. In the long term, to have renewable and essentially inexhaustible sources of energy for sustained economic growth (Reference 3). The latter objective, which includes wind power applications, is further explained in the National Energy Plan by the following statements.

> ... The use of nonconventional sources of energy must be vigorously expanded. Relatively clean and inexhaustible sources of energy offer a hopeful prospect of supplementing conventional energy sources in this century and becoming major sources of energy in the next. Some of these nonconventional technologies permit decentralized production, and thus provide alternatives to large, central systems (Reference 2).

> ... Wind can make significant regional contributions in the medium term. Wind systems can supply energy to small utilities, hydroelectric systems and dispersed users of power (Reference 2).

Major General Robert C. Thompson, former Director of USAF Engineering and Services Center, underscored the president's policy by stating that:

> ... Today's energy problem, like that identified in 1973, simply will not go away. Costs will continue to spiral and resources will become more scarce. Our actions as energy managers and technical experts will ultimately bear directly on force readiness around the world (Reference 3).

More recently, George Marienthal, Deputy Assistant Secretary of Defense (Energy, Environment and Safety) stated that:

> ... The overall defense energy program we have developed to manage this vital national resource is multi-faceted. It encompasses energy availability, energy conservation and energy technology applications. Our specific energy programs ...assure force readiness, minimize energy costs, and promote energy self-sufficiency on military installations. Effective implementation of these programs is critical in today's ever-tightening world oil supply. We plan to move away from the use of scarce energy resources to those that are more abundant and/or renewable (Reference 4).

Wind energy advertised as a non-polluting, non-depleting, environmentally benign alternate energy source would seem to fill the stated requirements. However, the sporadic and somewhat unpredictable nature of the wind makes careful study and special considerations essential before wind power can be efficiently extracted.

Aerospace technology of the last two decades promises increased aerodynamic and mechanical efficiencies when that technology is applied to wind machines. In addition, federal funding of wind energy projects has grown from a token amount in 1973 to a budget of $80 million in 1979. While the federal programs address many applications of wind technology, there are several areas unique to the Department of Defense not being considered. It is to the partial satisfaction of these unique applications that the present project is dedicated.

3. PROJECT HISTORY

At project inception in early 1977, it was envisioned that a commercially available vertical axis wind turbine (VAWT) rated at approximately 8 kW would be procurred. Output from the VAWT would be directed to a water storage tank in which the water temperature would be raised using resistance heaters. The heated water would then be

circulated through a small building designed using state-of-the-art energy conservation measures. Linking the use of a unique alternate energy source with sophisticated conservation measures was thought to fit both areas of Air Force energy interest.

Late in 1977, however, it became obvious that the project should not proceed in this direction because:

a. The manufacturer of the only commercially available VAWT was reluctant to sell his machine if it were to be used for water heating.

b. The VAWT test site selected and environmentally approved, while conveniently located, was too small to support a wind turbine of the selected size.

c. Energy conservation and conversion efforts were underway at numerous other agencies and, thus, USAFA efforts would be duplications.

Therefore, the following changes in project direction were taken late in 1977 to correct the above listed deficiencies.

a. In the face of non-availability of a commercial machine, a VAWT would be designed, fabricated, and tested in-house.

b. Size of the VAWT would be scaled down to fit the test site and simultaneously respond to a unique mission support role.

c. Energy conservation and conversion aspects would be dropped from the project. Power output from the VAWT would be measured yet not used in any specific manner. Once power output was established, it was deemed a simple matter to apply the output to a specified task.

d. The USAFA VAWT would be designed to meet certain requirements under the BARE BASE concept. Certain aspects of BARE BASE needs were not being addressed by other VAWT designers.

Focus on the vertical axis design versus conventional horizontal wind machine was continued through the course of the project because:

a. Experience in the operation of horizontal wind turbines was being gained on an Air Force owned and operated Grumman Windstream Model 25 at F. W. Warren AFB, Wyoming.

b. Studies by Sandia Laboratories showed promise for the vertical axis wind turbine and provided a foundation of technical design information.

4. PROJECT OBJECTIVE

The present objective of the USAFA Wind Energy Conversion System Project is to design, fabricate and test a small vertical axis wind turbine to meet a unique requirement under the BARE BASE concept.

5. APPROACH

The United States Air Force mission requires that tactical aircraft operate from previously unprepared airfields in remote worldwide locations on short notice. Such airbases are quickly brought to operational status using equipment and support facilities airlifted to the site by large strategic and tactical transport aircraft under what is known as the BARE BASE concept. The very nature of this mission dictates that all equipment be compact, portable, efficient, and easily installed upon arrival. Electrical power requirements for all tasks from space heating to aircraft electronics repair is presently provided by conventional fossil fuel generators.

The Air Force Engineering and Services Center is addressing those areas of Air Force operations where fuel savings may be realized through the application of alternate energy sources. One possible area for such savings is the electrical power requirements of the BARE BASE concept. For example, a wind energy conversion system might well be applied to such tasks as the heating of living quarters or the cooking of meals where stringent quality controls on the power required do not exist. The USAFA VAWT design addresses this application. To support this design goal, the following approach was taken:

a. VAWT components are relatively light for ease of field handling.

b. VAWT installation is accomplished using hand tools and no heavy equipment or concrete.

c. Aerodynamic rather than electrical starters are used on the generally non-self-starting main blade system to conserve power produced and increase self-sufficiency.

d. Variable rpm operation through alternator field modulation is employed to maximize power output.

e. Steps are taken to protect the turbine from severe weather phenomena such as lightning and sandstorms.

It should be mentioned that existing components and simplified analyses consistent with good engineering practice were used in the design and fabrication processes. This is not surprising when dealing with a technology blessed with centuries of history and the benefits of modern aerospace developments. The recent results of Department of Energy sponsored studies on vertical axis wind turbines at Sandia Laboratories, Albuquerque, New Mexico, were used extensively in the present design.

SECTION II

USAFA VAWT DESIGN

1. INTRODUCTION

The wind turbine design described in this section and shown in Figure 1 was tailored to the design approach and goals of Section I. In addition, the sizing of the machine and its associated accessories was driven by the size of the turbine test site but more important by the prime mover (main blades and shaft set) acquired from a Denver-based inventor late in 1977 (Reference 5). This prime mover consisted of two main blades, the set having a height-to-diameter ratio of 1.0, with a blade-plane diameter of 3.66 m (12 ft). In the absence of commercially available blades or the machinery to fabricate a blade set in-house, this acquistion provided a starting point for completion of a functional prototype.

2. TOWER

Following procurement of the prime mover, the support tower (between the blade and shaft set and ground level) was designed. Considerations in the design were:

a. Raise the prime mover high enough to clear adjacent obstructions and yet remain low enough for maintenance of accessories inside the tower.

b. Provide room inside the tower structure such that all accessories (braking system, alternator, vibration sensor, etc.) could be shielded from the environment.

c. Withstand the design loads from guying, prime mover and dynamic torque while still being lightweight.

d. Interface easily with the foundation design.

The resulting tower design shown in Figure 2 is a standard triangular truss structure 2.13 m (7.0 ft) high and 0.39 m (15.25 in) on each of its sides. The three vertical members are 5.08 cm (2.0 in) hollow steel tubes while all other members are 2.54 cm (1.0 in) steel angle stock. Full length sheet aluminum weather covers with doors for accessory servicing shield the tower interior from severe weather conditions. A check of the tower design using a three-dimensional finite element truss model showed the maximum in-service stress in any member to be 12.6 MPa (1826 psi).

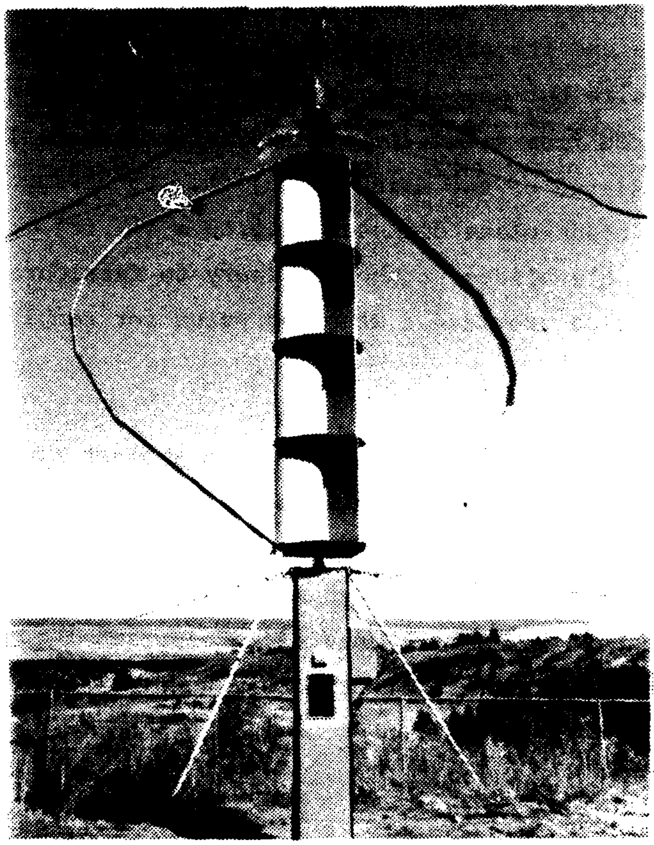

Figure 1. USAF Academy Vertical Axis Wind Turbine

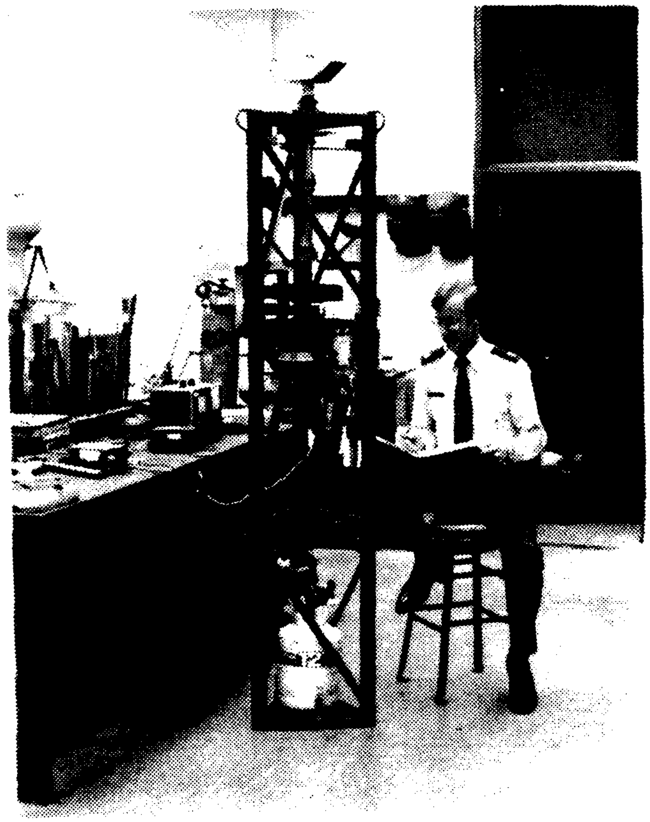

Figure 2. Support Tower

3. TOWER FOUNDATION

Since the tower foundation must also meet the goals of portability and ease of installation, unusual requirements were placed on its design. It must:

a. Adequately support in-service vertical loads and torque at any location on the USAFA installation.

b. Be capable of being carried to the site and installed by one man using common hand tools and no concrete.

c. Interface easily with and provide a leveling capability to the tower structure.

Soil profiles and engineering characteristics on the USAFA have been well described by Varner and Scott (Reference 6). While these characteristics vary somewhat across the installation, the vast majority are silty sands showing very little plasticity. Conservative values of Standard Penetration Value (N-count), unit weight and angle of internal friction were used in all calculations.

To resist the in-service torque, the foundation shown in Figure 3 was equipped with three vertical steel blades to provide passive resistance to rotation. A blade width of 25.4 cm (10 in) was selected to extend slightly past the tower vertical members and calculations suggested by Peck, et al (Reference 7) produced a required blade height of 29.2 cm (11.5 in).

The bearing capacity of the foundation necessary to resist in-service vertical loads came from the blades mentioned above and a steel T-beam welded to the top of each blade and resting on the surface of the soil. Sizing of the T-beam with calculations from Peck, et al (Reference 7) showed that the selected 7.62 cm (3.0 in) T-beam was more than adequate for the design loads.

The tower interface was accomplished with three vertical threaded studs welded to the T-beams. The tower simply slides over these studs and is adjusted to vertical with large nuts which are safety-wired in place.

Foundation installation is easily accomplished using only a shovel and sledge hammer. First a hole is dug to a depth less than the length of the blades and wide enough to accommodate the entire foundation. Next, the foundation is "set" by driving with the hammer to a depth where the flange of the T-beam is at ground level. Finally, the hole is back-filled and tamped.

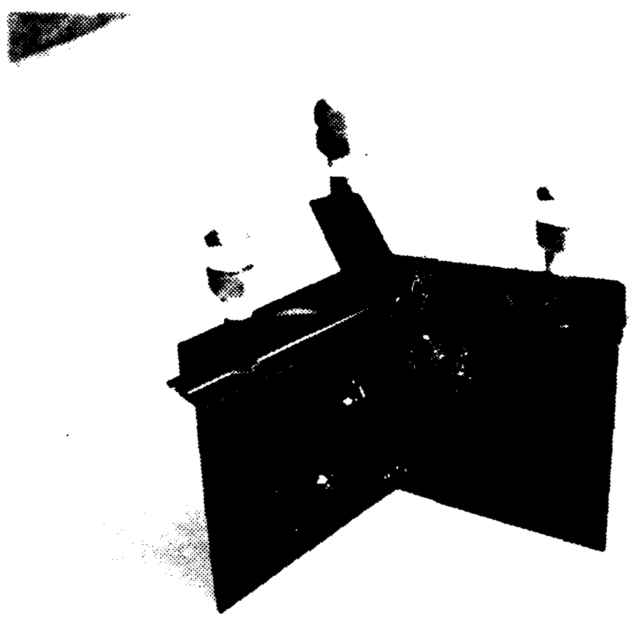

Figure 3. Tower Foundation

The success of this foundation design and installation procedure was shown in its performance through the structural failure described in Appendix A. Under the unknown yet severe loading which occurred, no evidence of any foundation failure was found and no shifting was noted.

4. GUYING SYSTEM

As with the tower and foundation, the guying system design also supports the approach and goals of Section I. The foundation was designed to resist in-service vertical loads and torque but not tower overturn, thus the tower required guying. Similarly, the main blade shaft turns in spherical roller bearings which permit pivoting from the vertical and thus also requires guying. The result is two sets of guy cables from tower and main blade shaft tops terminating in ground anchors.

A three-cable support was selected as the minimum required for structural intergrity yet still providing ease of installation. The guying angle to main shaft top is 35 degrees from the horizontal while the tower top is guyed at about 55 degrees. Due to the irregular and narrow nature of the test site, the east or downhill guy is raised by a steel A-frame to clear the rotating main blades. All six cables (three to tower top and three to main shaft top) terminate at ground level to three common ground anchors. Heavy turnbuckles (two at each ground anchor) permit leveling of the entire VAWT structure and proper cable tensioning. All cables are 0.635 cm (0.25 in) diameter 7 x 19 galvanized aircraft cable.

The main shaft-top cable's upper connection is to a deadend porcelain insulator (part of the lightning protection system) through a clevis. The ground anchor connection is with a turnbuckle secured by two cable clamps. The cable to the tower top is secured with a thimble clamp and a cable clamp to rings welded to the tower. The ground anchor connection is similar to that of the tower top cable. Actually, both cables terminate at a locally fabricated clevis rather than the ground anchor rod eyelet to allow room for turnbuckle adjustment. A safety cable is threaded through and fastened around the ground anchor connection to prevent static collapse if any of the connections fail. In the same fashion, and for the same reason, a nylon rope is tied around the main shaft top clevis/insulator connection.

The southerly main shaft guy is instrumented with a specially designed load-cell turnbuckle. Connection of a strain measuring indicator to the

load cell output permits very accurate tensioning of the upper cables to the selected 2224 N (500 lb) level. The lower cables are set to the same loads using a hand-held portable measuring device of local design.

As in the foundation design, ground anchors for the guying system were selected based upon requirements for strength, portability and ease of installation using common hand tools. Calculations suggested by Bowler (Reference 8) for a shallow foundation subject to shift showed that an expandable 20.3 cm (8 in) diameter anchor and 1.5875 cm (0.625 in) galvanized anchor rod at a depth of 0.91 cm (3 ft) would be adequate to a factor of safety of 2.5. Installation of the anchors begins with the digging of a slanted hole using a posthole shovel. The retracted anchor is placed in the hole and a heavy steel pipe forced repeatedly against the anchor sets the blades into the sides of the hole.

5. BEARING SELECTION

The USAFA VAWT bearing system was designed to allow all moving parts to move freely, to resist vertical and horizontal loading, to require relatively little maintenance during the testing life of the machine and to meet the requirements of the selected installation method. The final design includes three sophisticated roller bearings on the main shaft and five ball bearings on the drive train inside the tower. All shafts to which the bearings mate are of nominal 2.54 cm (1.0 in) diameter.

The five ball bearings integral to the tower require little comment. Their purpose is simply to allow free rotation of all drive train components and resist radial loads due to timing belt tensioning.

The three spherical roller bearings on the main shaft serve a somewhat different purpose. The one bearing mounted on the tower top and supporting the lower drive shaft of the main rotor system is designed to resist the vertical (thrust) loading due to main blade and starter bucket weight plus the vertical component of cable tension. It also must resist a much lower magnitude side (radial) loading from the wind and a fluctuating aerodynamic load during VAWT operation. This type of bearing accepts a small shaft tilt from true vertical which eases installation of the main shaft assembly and is forgiving in service. This same characteristic (and the desire to use common bearings) produced a design using two of the spherical roller bearings on the upper main shaft attachment as shown in Figure 4. Here, the bearing

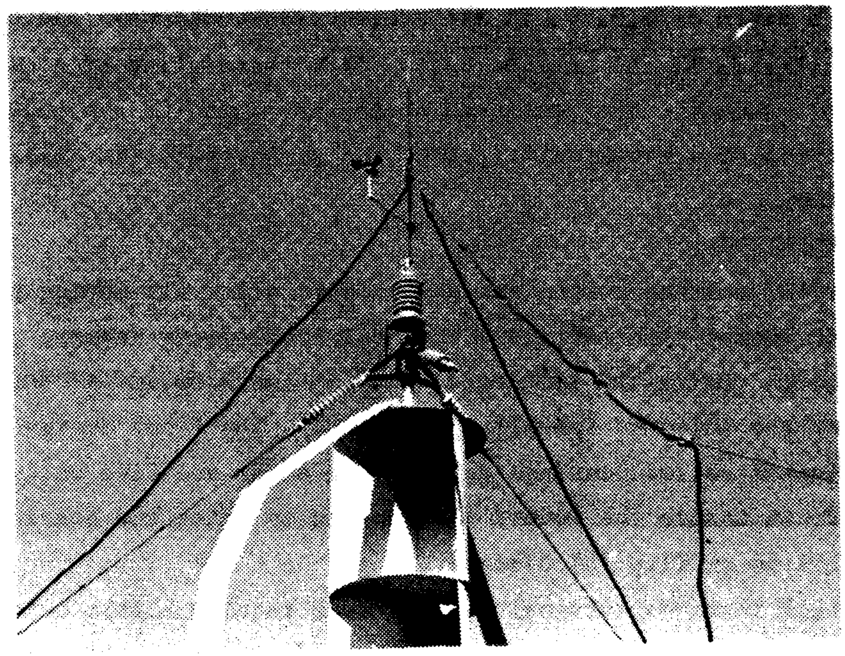

Figure 4. Upper Main Shaft Assembly

mount had to remain in perfect alignment with the rotating shaft since this mount also serves as a guy cable and lightning protection system attachment point.

Bearing maintenance has been minimal during the term of this project. Normal greasing on an annual basis has been accomplished. Some moisture absorption or bearing dryness has been seen. The spherical roller bearings are not completely sealed against severe environmental conditions and should be so protected in an operational design.

6. STARTING SYSTEM

Except in unusual circumstances, VAWT main blades of the Darrieus type are not self-starting. Therefore, some means of spinning the main blades to an rpm at which they produce positive torque is required. To support the goal of maximizing VAWT output, the design concept of aerodynamic starters mounted to the main shaft was selected. Other means of starting, such as an electric motor drive, have been used on other machines but require use of a portion of the electric energy the VAWT produces.

Wind tunnel testing at Sandia Laboratories (Reference 9) resulted in the conclusion that a two-bucket Savonius-type arrangement with gaps at the rotating shaft was most efficient; however, a three-bucket design was used in the USAFA VAWT as a compromise resulting in increased structural integrity. More details on the design procedure employed here are found in a technical paper by Oliver and Nixon (Reference 10).

The starter buckets as shown in Figure 1 are 81.3 cm (32 in) in diamter and 358.1 cm (141 in) long. They are an integral part of and are rigidly attached to the main shaft. The entire main shaft assembly can withstand a compressive load of 734 kN (165 kips) and has a critical shaft speed of 6,780 rpm. Total shaft weight is 1560 N (350 lb) where the slight weight penalty is offset by a large increase in structural rigidity. A starting torque of 6.8 N·m (5.0 ft-lbs) in a wind speed of 6.3 m/s (14 mph) is sufficient to overcome static friction in the drive train.

7. MAIN BLADES

The main blade set is comprised of two troposkien-shaped blades oriented at 180 degrees to one another. Each blade was fabricated from SAE 1008/1010 streamline steel aircraft tubing pressed to a NACA 0015 airfoil shape. Straight sections of tubing were welded together to closely approximate the

desired troposkein shape. Each joint was internally reinforced in addition to butt welding. End fittings to accommodate a four-bolt connection to the starter buckets were then welded on. A brass trailing edge, epoxied in place, completes the airfoil shape. The entire blade was coated with special rust-preventative paint. The finished blade chord length is 12.7 cm (5 in).

A "worst case" analysis of blade loading showed in-service maximum stresses to be less than half of the yield strength of the blade material. In addition, operation to 350 rpm, well above the maximum rpm expected, would produce a maximum stress below the fatigue limit.

8. ALTERNATOR

A 110 VDC alternator was selected to convert the main shaft mechanical energy into electrical energy. This device displays high efficiency at relatively low rpm with maximum output of 1200 watts over a range of about 1000 rpm to 3000 rpm. This alternator was supplied with heavy duty bearings, self-excited field and a self-contained rectifying circuit.

Early laboratory testing was conducted to confirm the power output and efficiency curves supplied by the manufacturer. In addition, this testing showed that externally commanded field excitation was feasible and would allow a large measure of control over the mechanical shaft input. Once these general characteristics were established, the support structure interior to the tower was designed.

A single pin support allows the second stage speed increaser belt, which terminates at the alternator, to be tightened independent of the first stage. Rectifier diodes have been moved to a separate mount outside the alternator case for ease of replacement (several diodes have failed in service, probably due to the severe test environment). A final addition to the alternator was an rpm sensor consisting of a notched disk fixed to the alternator shaft and an optical sensor. Rpm output is subsequently fed to the software through an analog channel as a key input to the VAWT control scheme.

9. SPEED INCREASER

Since the alternator is most efficient in the 1000 to 3000 rpm range and the VAWT main shaft operating range is about 100 to 250 rpm, a speed increaser is required. A specific ratio of 9.52:1 was selected from a match of the test site wind energy density, the main shaft rpm range and the alternator efficiency.

A trade-off study between speed increaser types (gears, chains and timing belts) resulted in the selection of a driving belt/sprocket arrangement shown in Figure 5. The two stages are stacked where the first stage increase is 3.33:1 and the second is 2.86:1. A pivoting frame, extending slightly outside the tower, houses the two sprockets and permits easy tensioning of the first, or upper, stage belt. In a similar fashion, the second stage belt is tensioned by pivoting the alternator as described in the previous section.

10. BRAKING SYSTEM

a. General Background

A strong, reliable braking/overspeed control system is an absolute necessity on any wind machine. A vertical axis wind turbine can "run-away" to excessive speeds causing machine destruction. To preclude this occurrence, the USAFA VAWT has two independent braking systems, one mechanical and one electrical.

b. Mechanical Brake

The mechanical system has three major components. A brake disk with a single puck caliper is keyed to the rotor drive shaft inside the tower top as shown in Figure 6. The brake is applied by spring force on the caliper arm and released by overcoming the spring force. The second major component is a disk brake actuator. This actuator shown in Figure 7 is basically an air cylinder having an overcentering device and microswitch sensor attached. The third component is an air bottle or accumulator located at the base of the tower as shown in Figure 8 and connected to the actuator through an electrically positioned air solenoid. The sequences of events for brake application and brake release are described in Tables 1 and 2.

TABLE 1. BRAKE APPLICATION SEQUENCE

Step Number	Event
1	Brake actuator solenoid power removed
2	Overcenter device on actuator released
3	Spring force applied to calipers

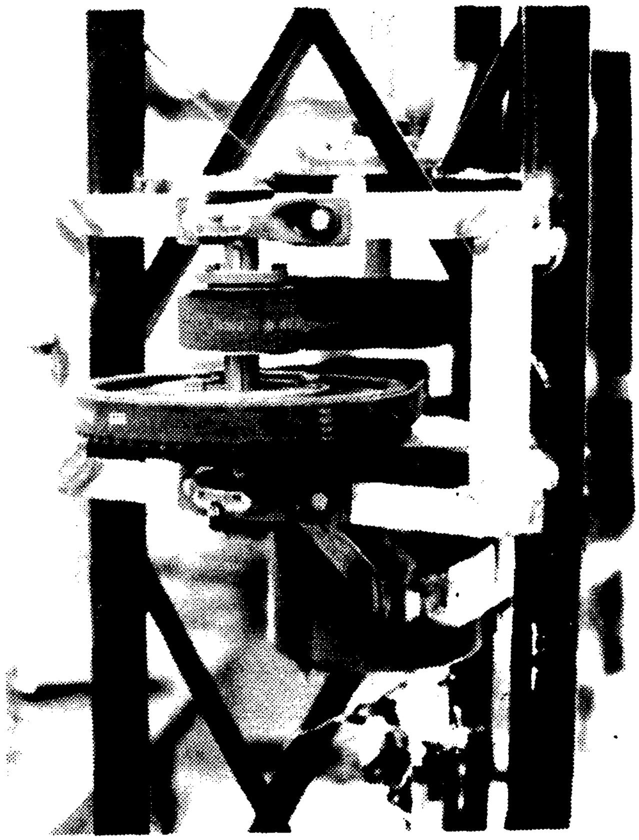

Figure 5. Speed Increaser

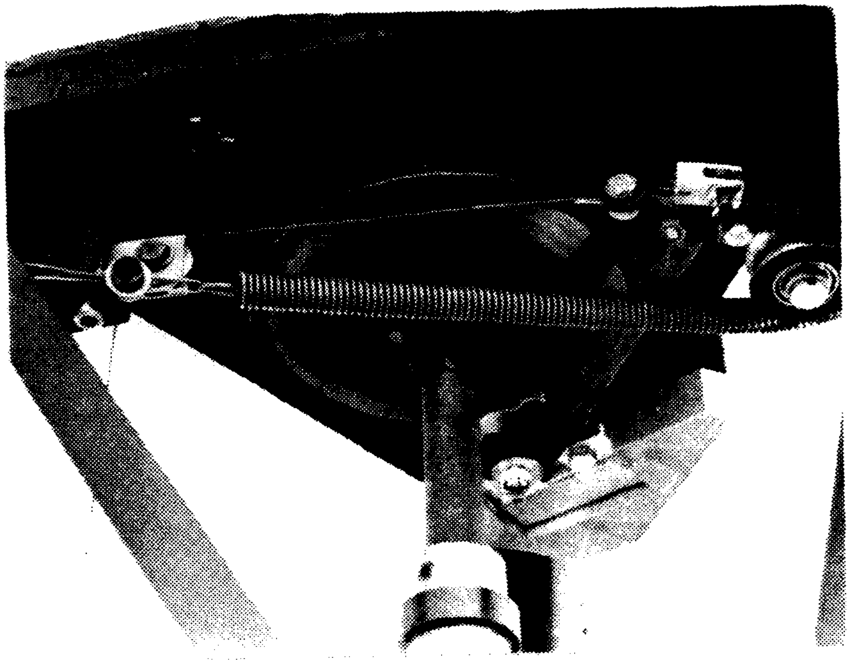

Figure 6. Disk Brake Assembly

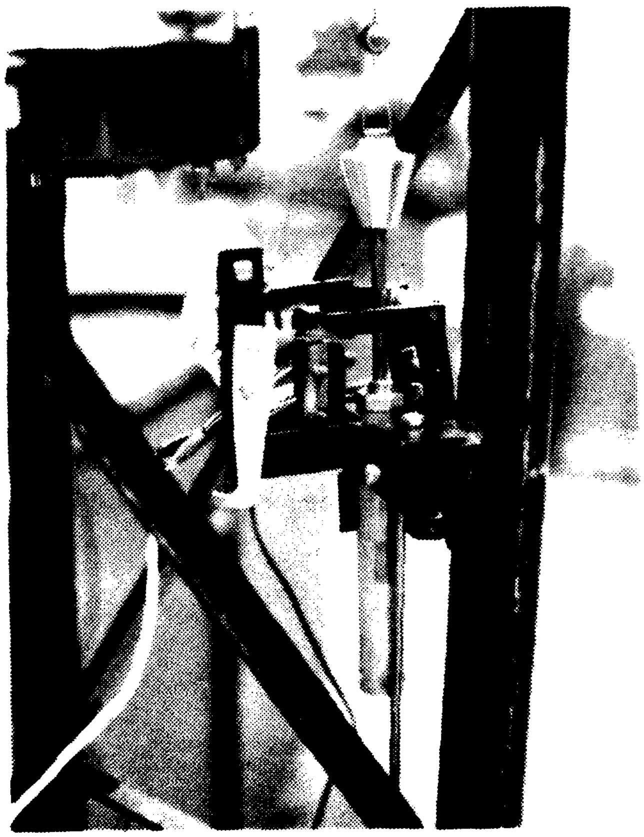

Figure 7. Disk Brake Actuator

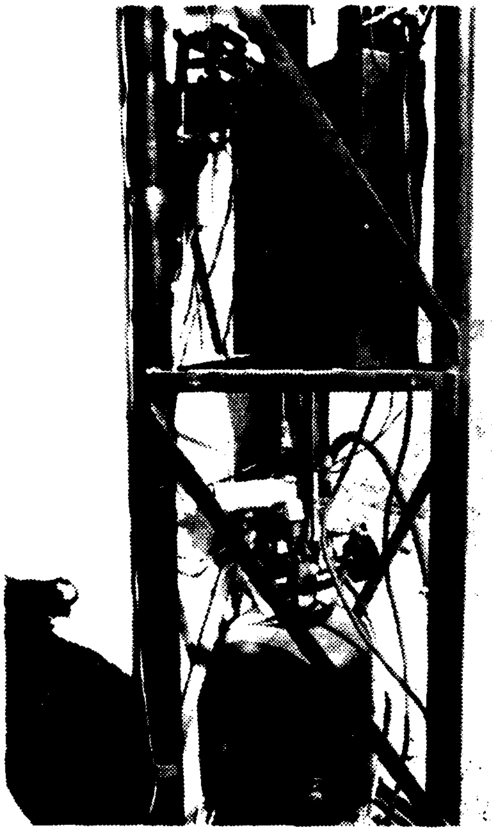

Figure 8. Disk Brake Accumulator, Solenoid and Actuator

TABLE 2. BRAKE RELEASE SEQUENCE

Step Number	Event
1	Signal from the control system opens the air solenoid
2	Air pressure from the accumulator forces the air cylinder down, overpowering the disk brake caliper spring
3	Power to the brake actuator solenoid holds the overcentering device so the brake cylinder remains down keeping the brake off
4	Power is removed from the air solenoid stopping the flow of air

There are several advantages to such a system. First, the air accumulator can be easily recharged from a portable tank of compressed air. Second, brake application will occur mechanically when, for any reason, power to the brake actuator solenoid is removed. Finally, the overcentering device permits the brake to be held in the released position using a solenoid with a very low power requirement (0.075 watt). Laboratory and field testing of the mechanical brake system has been extensive. Static and dynamic capabilities of the brake disk and caliper were first established using a bench test arrangement. All components were then attached to the tower, adjusted to fit, and the system was cycled. The number of cycles from full accumulator charge (100 psi) to a point where pressure was insufficient to overcome the brake spring force (about 45 psi) was tentatively established to be about 200 cycles. Specifics of these laboratory tests are not reported here since field test cycles are more significant and have not yet been recorded. In addition, the mechanical brake will be infrequently applied and released in automatic, unattended operation. Its function is to operate in extreme conditions and the turbine will be stopped (brake released), coasting (no power being generated), or producing power during most of its operational life.

c. Electrical Brake

The electrical braking system operates in conjunction with, yet independent of, the mechanical brake. Therefore, anytime a braking signal is received, both systems are commanded to the on position. As described earlier in the alternator section (II.8), VAWT control at either constant

tip-speed ratio or constant rpm is achieved by microprocessor commands varying the current across the alternator field windings. Electrical braking is accomplished by applying full or maximum field current resulting in slowing of the VAWT main shaft.

Both the mechanical and electrical braking systems have been satisfactorily field tested and compared to theoretical predictions. These test results are found in Section VI.2.

11. LIGHTNING PROTECTION SYSTEM

A lightning protection system was developed to protect the VAWT and associated electronics from damaging lightning strikes. For the purpose of lightning protection, the VAWT can be considered a high tower in an area of surrounding lower structures and the test site lies in a geographic area having the second highest frequency of thunderstorms nationally. In light of these environmental conditions and in the interest of protecting the sophisticated electronics and rotating components of the VAWT, the decision was made to design and install a lightning protection system.

A lightning strike on the top of the VAWT would be expected to travel to ground through the guy cables and/or main shaft/tower assembly. Damage in the form of pitted and welded bearings and destroyed electronic circuity could be expected. Protection from such a strike can be realized by channeling the current to ground around the parts to be protected. Two paths to ground seem practical with the present VAWT: (1) down the main shaft/tower and passing around bearings using a set of heavy brushes and rings; or (2) down heavy copper wires strung outside the rotor and connected to the guy cables. The latter approach, suggested by Reference 11 , was used in the USAFA VAWT lightning protection system.

Figure 4 shows the key features of the lightning protection system as installed. Positioned above the upper bearing mount is a porcelain vertical post insulator modified to accept a copper-clad 1.52 m (5 ft) lightning rod. Similar insulators of the "deadend" variety are attached between the three upper guy cables and the upper bearing mount. Completing the system is a set of three heavy woven copper cables clamped to the lightning rod and also clamped to the upper guy cables at a point outside the arc of the main blades. These three copper cables then drop vertically to be clamped to the lower guys, and finally terminate in a triangular closed circuit grounding net buried in the soil.

The primary consideration in this design was the sizing of the insulators in order to achieve some confidence that most lightning strikes would travel along the intended path. The nature of lightning is not yet well understood, but a search of the existing literature indicated a 200 kv insulator would probably be adequate for protection against 95 percent of typical strikes. A secondary consideration in the design was the connection of the system to adequate ground. Soil at the VAWT test site is a type of decomposed granite and defies the sinking of grounding rods by conventional means. Therefore, the grounding net described earlier was selected as a viable alternative.

The success of the USAFA VAWT lightning protection system is evidenced in two ways. First, after 2 years in service, there is no evidence of lightning strikes or lightning induced damage. Second, the system is structurally sound and has even survived a main shaft collapse (Appendix A). Following this failure, a redesigned shaft was installed and all lightning protection parts reattached. Even the porcelain insulators were reused after careful dye penetrant tests showed no cracking or chipping.

12. ANEMOMETERS

a. General Background

A key input to the USAFA VAWT is the wind speed. This parameter is used in the control scheme to determine if:

(1) Conditions are adequate for a turbine start.

(2) Wind speed exceeds safe operational limits.

(3) Alternator field must be increased or decreased to track at constant turbine tip speed ratio or constant rpm.

Two independent wind indicating systems at separate locations provide this information. Output from both systems is continuously displayed on the computer terminal screen and recorded on casette tapes during operational turbine testing. The mast-top anemomenter provides wind speed information only and is considered the primary input. A second stand-alone indicator located directly north of the VAWT and on a separate tower provides both wind speed and direction. This device is considered a back-up to be used during testing only.

b. Mast-top Anemometer

The mast-top anemometer is a three cap arrangement driving a self-contained alternator. The anemometer head is attached to the lightning rod

below the ground cable connection on an arm extending away from the upper assembly and about 1.22 m (4 ft) above the rotating blades (Figure 4). Output is fed through a two-wire cable passing down an upper guy cable and terminating in the electrical junction box internal to the VAWT tower. This anemometer head is very reliable and has operated without maintenance for a period of 2 years. A strong lightning strike would probably destroy the head in such case the software control program will call for turbine shutdown. As reported by Sandia Laboratories (Reference 12), the output from the mast-top anemometer is probably affected by disturbed air flow generated by the VAWT during operation. Efforts to correlate this anemometer with the stand-alone system are ongoing.

c. Stand-Alone Anemometer

An independent sensor is mounted on a 4.27 m (14 ft) pipe tower 9.14 m (30 ft) due north of the VAWT such that the head is level with the center of the turbine blades (Figure 9). This device feeds both wind speed and direction information to the control system and to a separate, continuously recording strip chart located in the instrumentation building. The strip chart output is useful as a recent past record during turbine testing and has been extensively analyzed as part of the USAF Academy Wind Site Survey.

13. VIBRATION SENSOR

a. General Background

Of five massive structural failures involving vertical axis wind turbines, the authors are aware of four caused directly by excessive vibration including one on the earlier model of the USAFA VAWT (Appendix A). The common scenario is one of the turbine operating rpm exciting a resonant frequency of the machine or one of its components. The resulting amplitude of vibration and subsequent high stress levels lead to machine collapse. In an effort to preclude another such failure of the USAFA VAWT, a vibration sensor was designed, tested and installed.

b. Sensor Design, Testing, and Installation

The basic sensor design follows the classic example found on the famous Danish Gedser Windmill (Reference 13). In the Gedser machine, a large steel ball rests on a vertical section of pipe. The ball is connected by a string to a Square-D type switch. Excessive vibrations cause the ball to

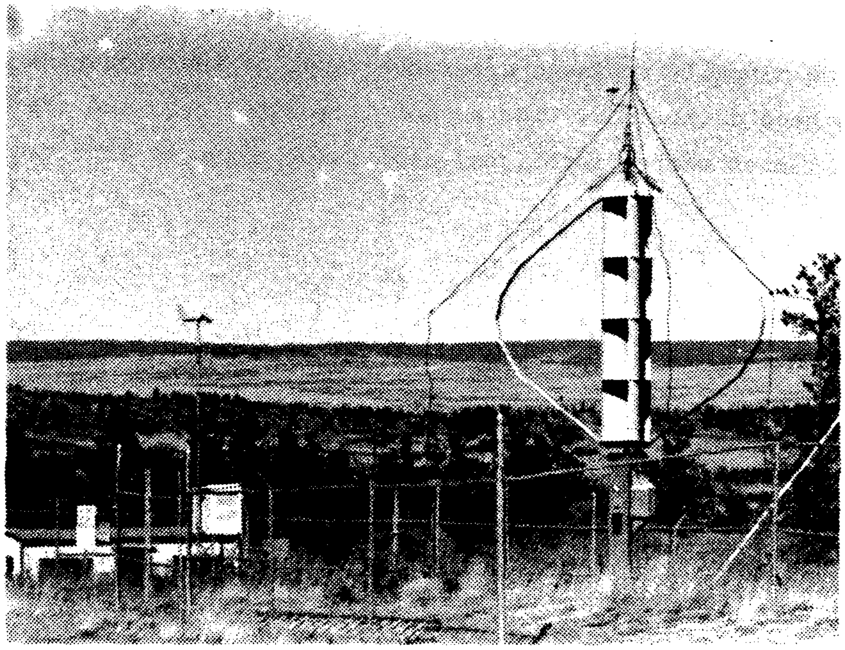

Figure 9. Test Site

fall off the pipe and pull the switch to the off position. In the USAFA VAWT design, the ball is mounted on a microswitch sandwiched between two aluminum mounting plates. Between the ball and switch is a loose-fitting plate having a hole to accept the ball. The hole size was "tuned" during laboratory shaker testing such that the ball falls off when vibrational amplitudes exceed 1.59 mm (0.0625 in) at a turbine speed of 250 rpm. This opens the microswitch, cuts all power to the VAWT, and applies the brake. An accompanying signal to the control system causes an indication at the computer terminal that the VAWT is in the "VIBES" mode. The VAWT does not automatically reset but rather the ball must be manually replaced after the cause of the vibration sensor triggering has been determined. The sensor is mounted near the top of the tower vertical member where vibrational amplitudes might be expected to be highest.

SECTION III

VAWT DYNAMIC ANALYSIS

1. INTRODUCTION

As with any piece of rotating machinery, consideration must be given to system dynamic response and interaction. A total system approach, while desirable, was not possible or practical nor has such an approach been attempted by other investigators to date for a VAWT. Rather, a component analysis was completed with special attention focused on areas where component natural frequencies might be close enough to cause coupling or be excited to resonance in the normal operating range of the VAWT. Interest in the present investigation was directed to the following areas:

a. Upper and lower guy cable frequencies as a function of tension and the potential for one and two-per-rev excitation by normal VAWT operation.

b. Main blade natural frequencies and mode shapes and the potential one and two-per-rev excitation by normal VAWT operation.

c. Blade flutter.

d. Potential for coupling between blade modes and between guy cables and blades.

2. GUY CABLE NATURAL FREQUENCIES

The natural frequencies of individual upper and lower guy cables were determined using a three-dimensional finite element program for a single span cable (Reference 14). Figures 10 and 11 show these frequencies as a function of the cable tension and indicate that the difference between the natural frequencies of the upper and lower guy cables is less than 2 percent at all cable tensions. Figure 12 shows the first two natural frequencies as a function of cable temperature assuming an installation tension of 2220 N (500 lb) at 21°C (70°F). While it might appear from the figure that the cables would not be excited in resonance in one-per-rev normal operation, two-per-rev excitation could still occur.

High initial cable tensions were considered to raise frequencies above two-per-rev levels during normal VAWT operation yet this was not deemed practical due to the excessively high tension required for the range of operating temperatures expected. Additional factors considered in the

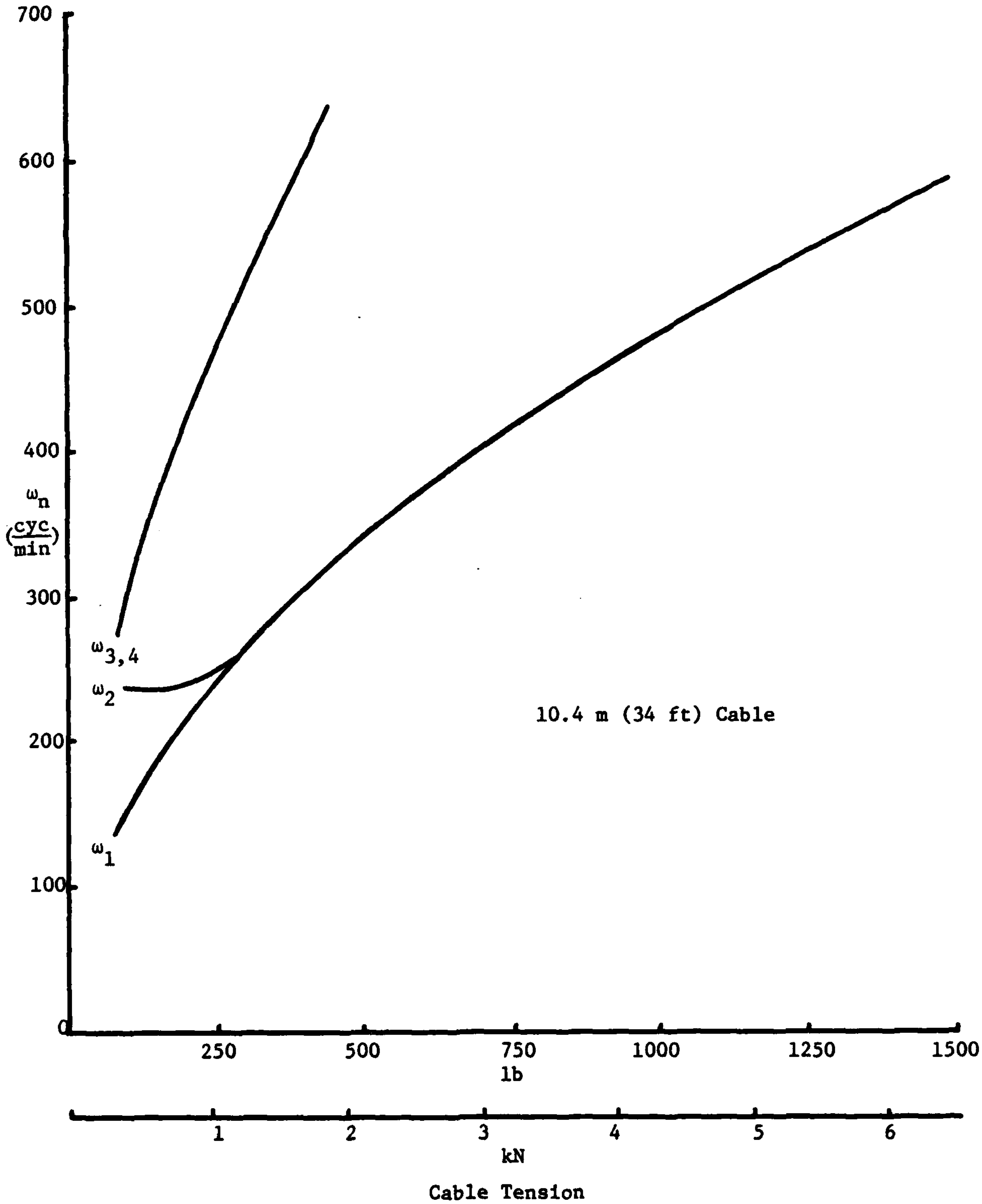

Figure 10. Upper Guy Cable Natural Frequencies

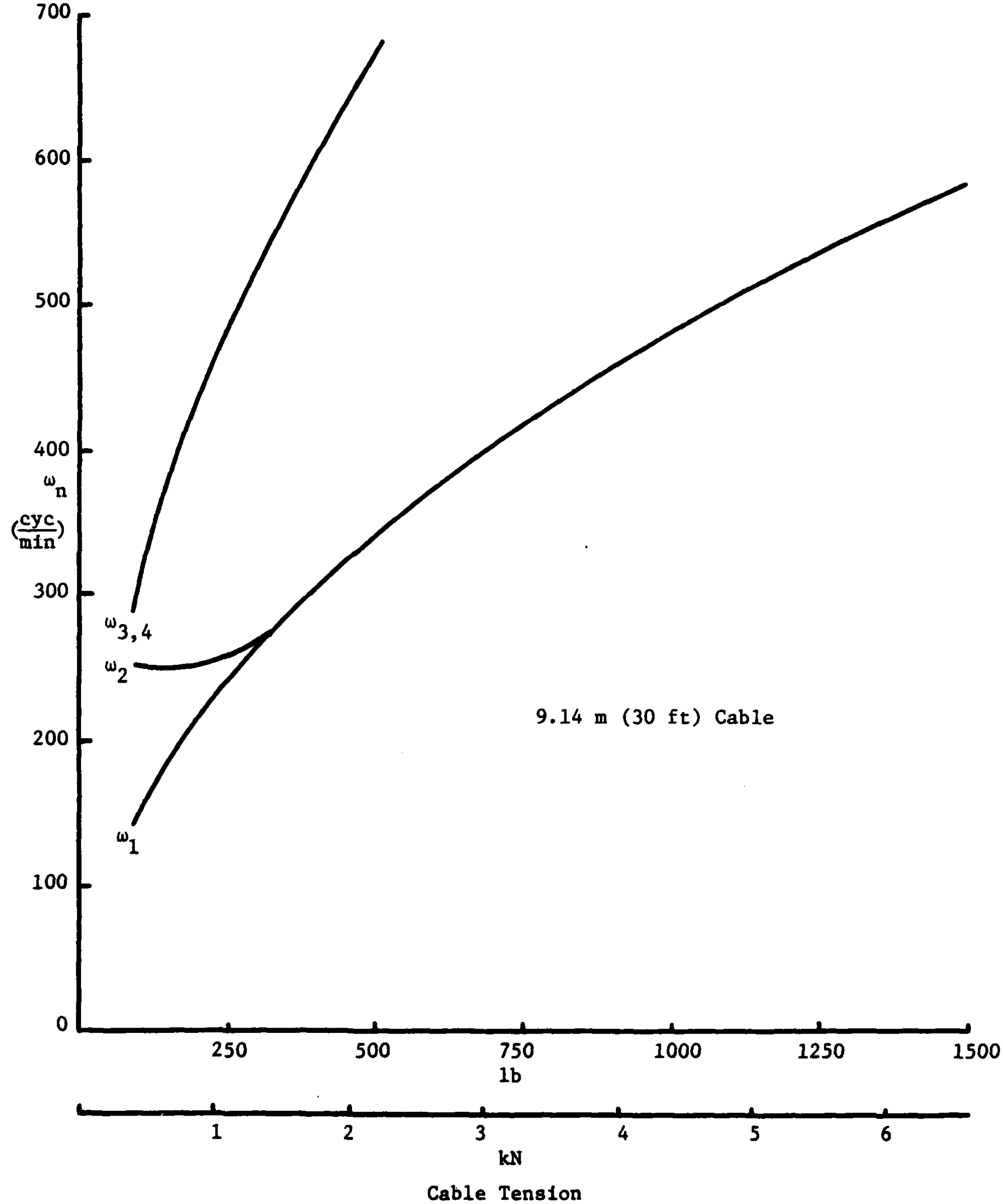

Figure 11. Lower Guy Cable Natural Frequencies

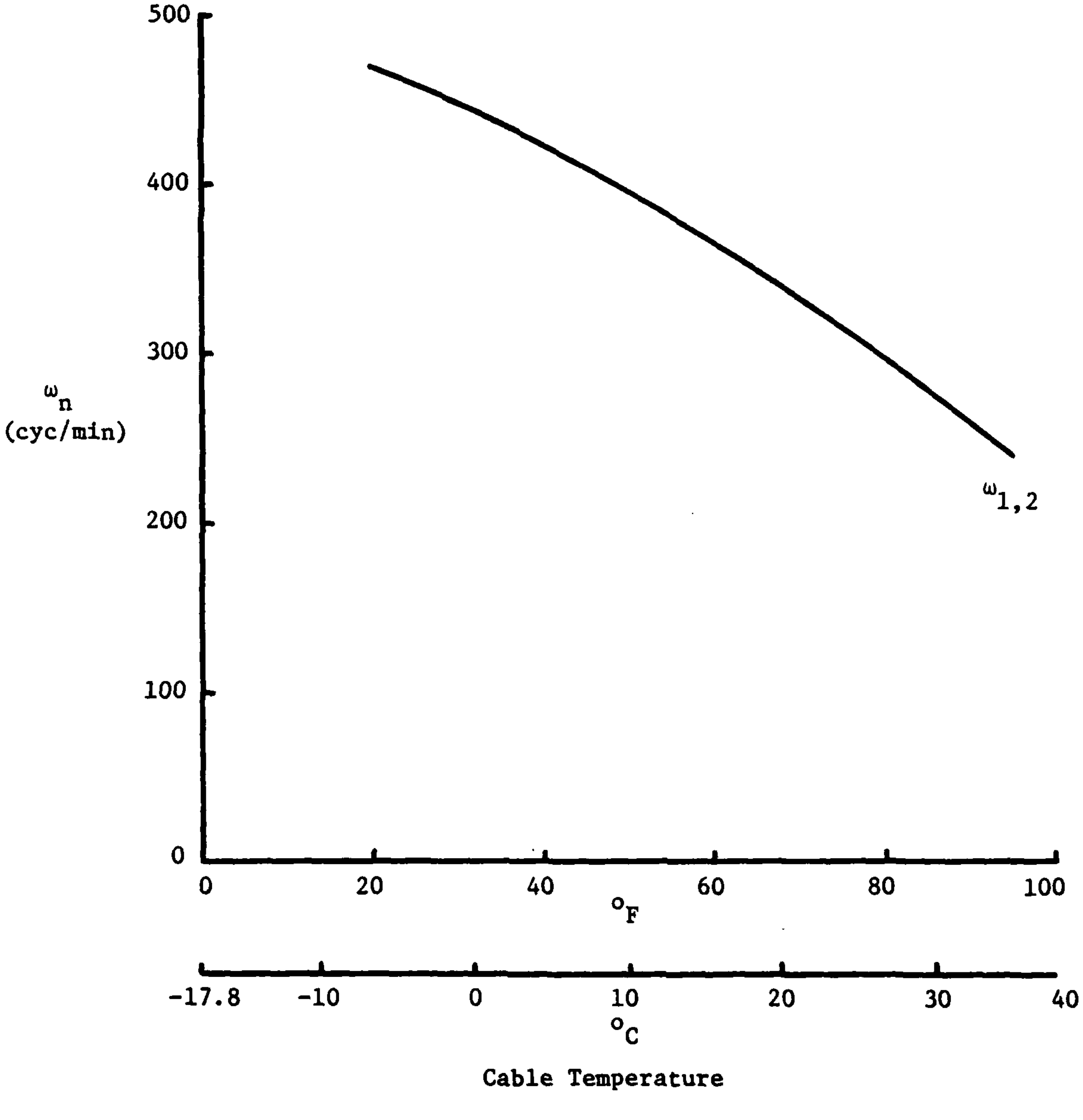

Figure 12. Guy Cable Natural Frequencies as a Function of Temperature, First Two Modes

selection of the 2220 N (500 lb) initial tension were:

a. Terrain features at the VAWT site cause individual cable lengths to differ thus reducing coupling possibilities.

b. Heavy copper lightning protection system ground cables are tied to all guy cables and should provide some damping.

c. During operational VAWT testing, monitoring of dynamic cable tensions using the load cell showed only a small variation in tension in the area of the fundamental cable frequency.

3. BLADE NATURAL FREQUENCIES AND MODE SHAPES

The natural frequencies and mode shapes of the blades were determined using standard finite element methods. A six degree-of-freedom beam element was used to generate the blade stiffness and mass matrices, which in turn were used in a general equation solver to determine the Eigenvalues and Eigenvectors of the blades in bending. The lowest natural frequency for fixed-fixed end conditions was found to be 505 cycles per minute (rpm), well above the turbine cut-out speed. The first three shapes and the corresponding frequencies are shown in Figures 13, 14, and 15. Similar results were obtained for pinned-pinned end conditions with the fundamental frequency lowered to 344 cycles per minute (rpm). While the present VAWT cut-off speed is about 250 cycles per minute (rpm), preliminary calculations indicated blade resonance might occur with pinned end conditions. Therefore, the fixed end design was retained.

4. BLADE FLUTTER

Flutter speeds were calculated using simplified procedures suggested by Ham (15). Due to the stiff nature of the blades, calculated flutter speeds are above both one and two-per-rev excitation speeds for operation of the VAWT to the 250 rpm limit. Therefore, blade flutter is not expected within the normal operating range of the turbine.

5. COUPLING POTENTIAL

Figure 16 shows a compilation of blade and guy cable natural frequencies as a function of VAWT rotational speed. Superimposed on the figure are one and two-per-rev excitations and the VAWT operating limit. First and second blade flatwise bending frequencies begin at values discussed in Section III.3 and are shown to be centrifugally stiffened with increasing VAWT operating speeds (Reference 15). The first blade chordwise frequency was

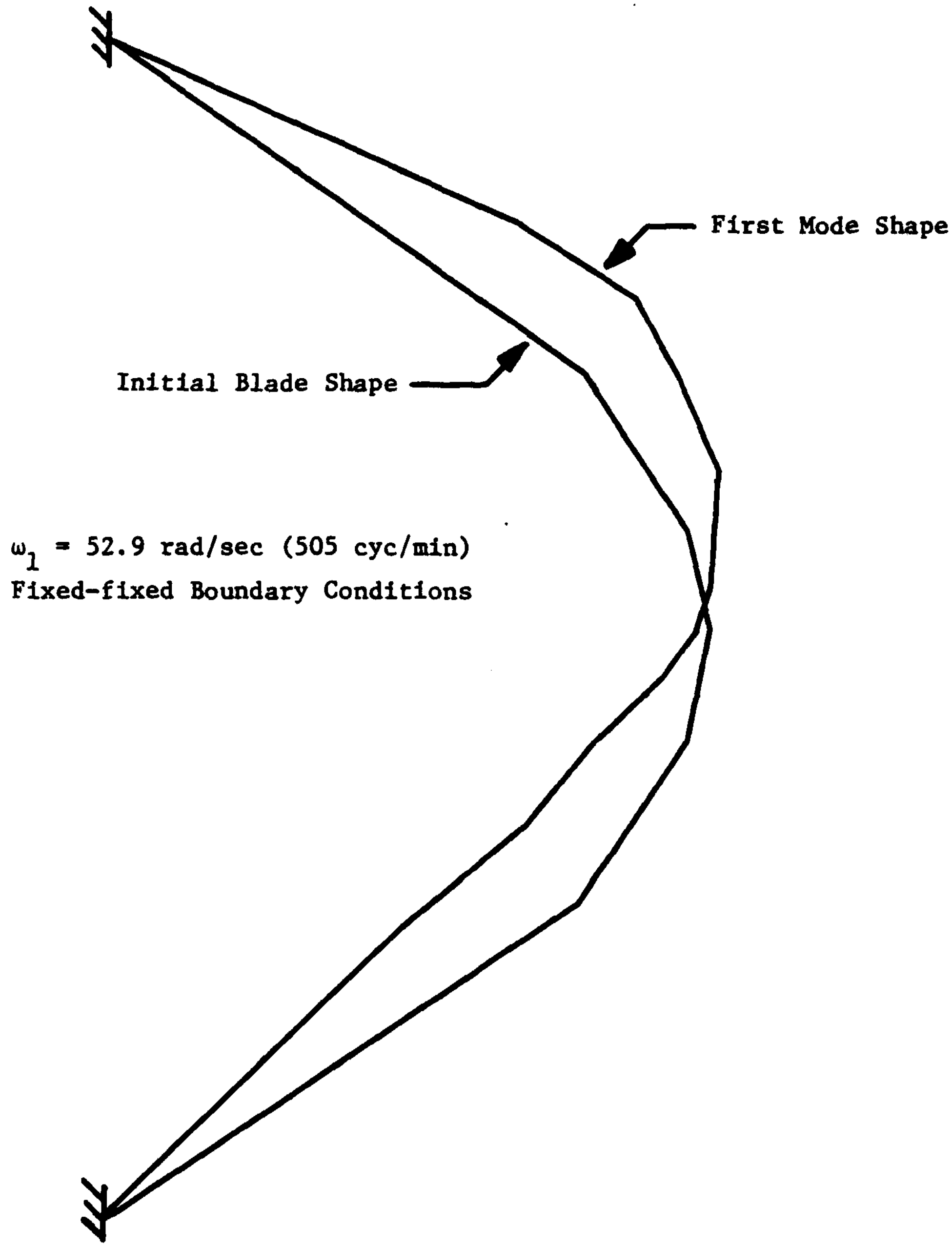

Figure 13. Blade in Flat-wise Bending, First Mode Shape

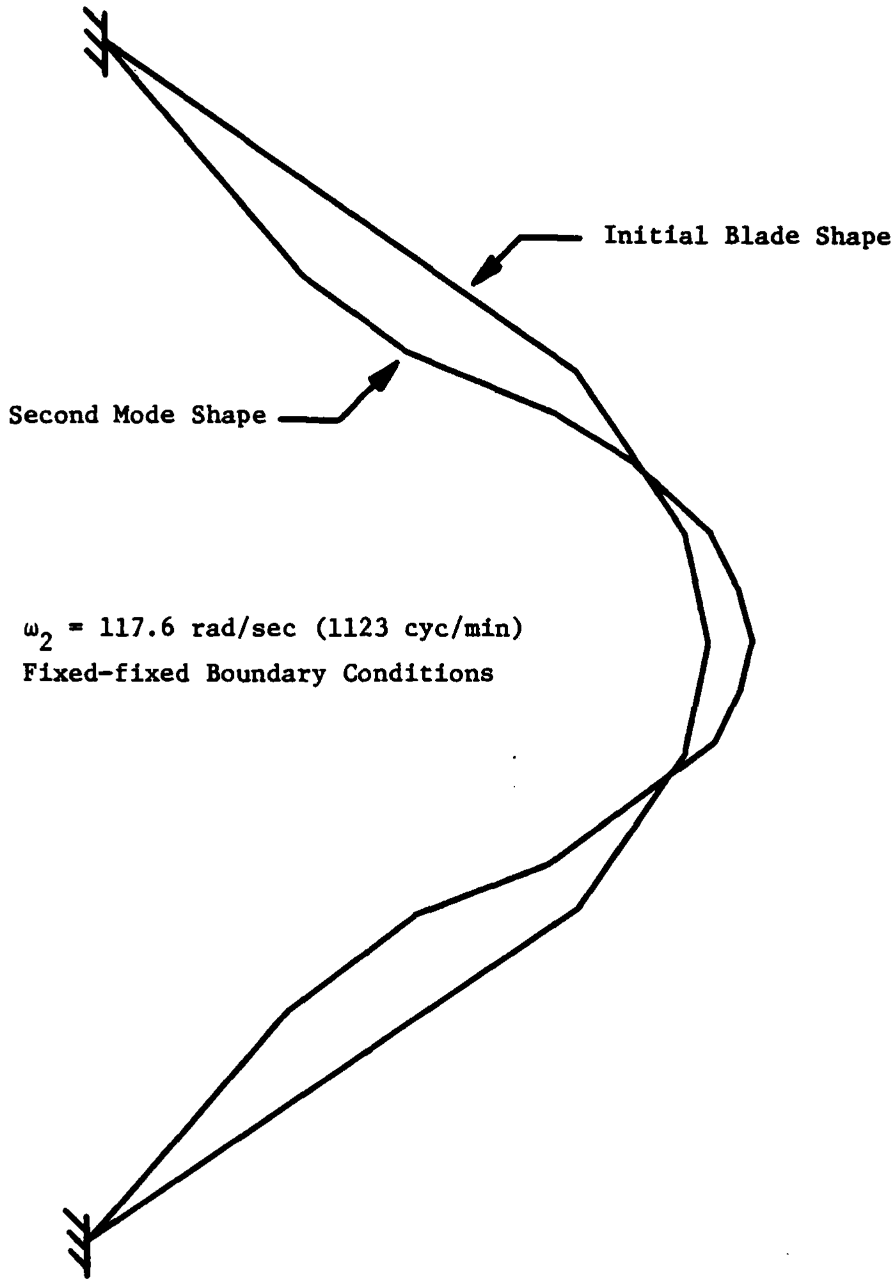

Figure 14. Blade in Flat-wise Bending, Second Mode Shape

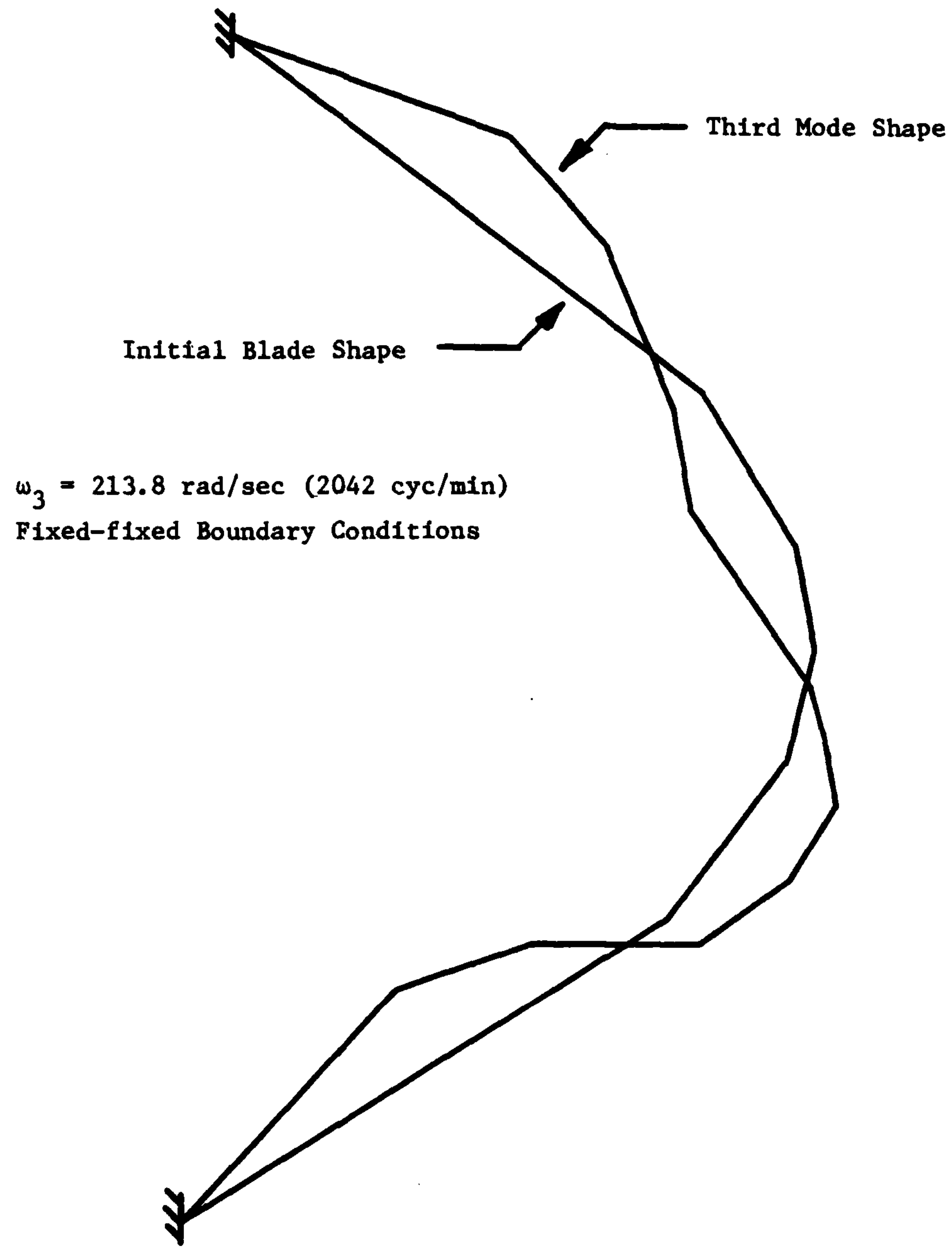

Figure 15. Blade in Flat-wise Bending, Third Mode Shape

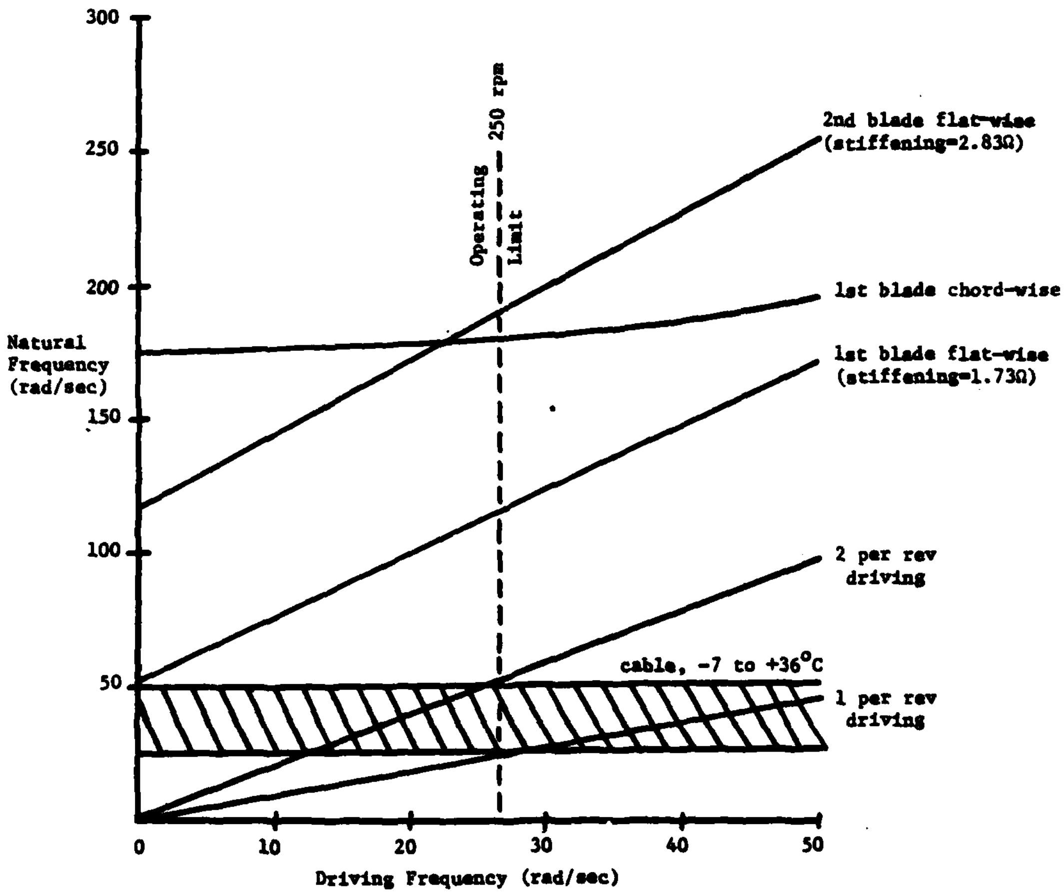

Figure 16. Vibrational Coupling Potential

estimated using a simplified spinning semi-circular shape (Reference 15). A guy cable frequency band for an initial tension of 2220 N (500 lb) and varying temperature is also superimposed on the figure (cross-hashed area). Inspection of this figure shows the potential two-per-rev guy cable excitation discussed in Section III.2. Possible coupling is also indicated between the first blade chord-wise and second blade flat-wise modes within the operating range. However, these modes are orthogonal and thus will not couple. Coupling of blade mast and support tower or between blades and blade mast was not considered an important consideration due to the extremely stiff nature of blade mast and support tower.

SECTION IV

VAWT INSTALLATION

1. GENERAL BACKGROUND

As a test of the design goals of a relatively light, portable wind machine installed using common hand tools, actual erection of the USAFA VAWT was accomplished as in a field environment. However, since this is a prototype, one-of-a-kind device, all components were first assembled and adjusted in a laboratory environment and then disassembled for transportation to the test site. A detailed field assembly plan was developed in the laboratory and used during machine installation. All VAWT components were transported to the test site by pickup truck but were on and off-loaded by hand. Actual installation occurred in three stages over a period of three consecutive days.

TABLE 3. VAWT INSTALLATION SEQUENCE

Day Number	Activity
One	Foundation and three guy anchors installed
Two	Tower positioned and guyed, some internal tower accessories installed
Three	Main mast and blades assembled, winched into position and guyed

This procedure could probably be condensed to one day for a similar production machine installed by an experienced crew of four.

2. FOUNDATION INSTALLATION

The small steel tower foundation was installed using a hand shovel and sledge hammer. First, a shallow hole was dug to accommodate the foundation. Next, the foundation was positioned and seated such that the device was level as shown in Figure 17. Finally, the hole was filled and the soil was tamped to hasten cohesion.

3. GUY ANCHORS INSTALLATION

Guy anchors and foundation installation are equally simple. Since the test site is in irregular terrain, a survey was first conducted to determine anchor placement. At the three anchor locations, a hole inclined at the

Figure 17. Foundation Positioning

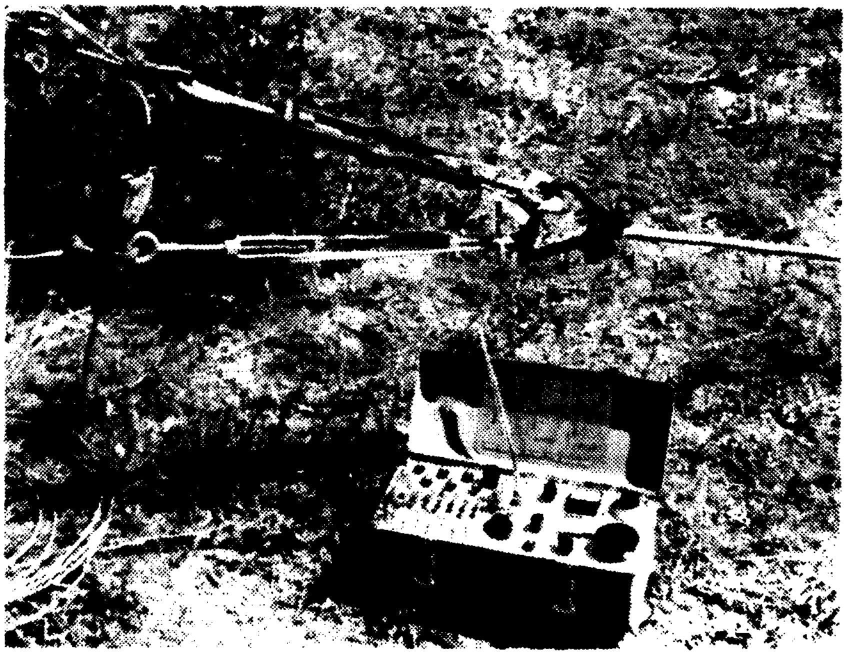

Figure 18. Upper Guy Cable Load Cell

calculated guy cable angle was dug using a hand post-hole shovel. Differing soil conditions caused hole depth to vary from about 1 to 2 meters. The 3.15 cm (8 in) diameter expanding ground anchors were then placed in the holes and the "ears" of each anchor were driven into the sides of the hole using a hollow steel mandrel positioned over the anchor rods. Back filling and tamping completed the process. One anchor is equipped with a special turnbuckle which, when connected to a strain indicator as shown in Figure 18, gives cable tension on the upper set of guy cables. This tension is monitored regularly and the cable tension is adjusted as necessary.

4. TOWER PLACEMENT AND ACCESSORY INSTALLATION

Once the tower foundation and guy anchors were in place, the tower was installed. The hollow vertical tower tubes were positioned over the studs on the foundation. Adjustment to vertical was accomplished with large nuts on a threaded portion of these studs, and the nuts were safety-wired to prevent slipping. The tower was then guyed to the three ground anchors and cable tension adjusted. All accessories internal to the tower (braking system, alternator, drive train, etc) could be installed at this point or after the main mast and blades are installed. In the test case reported here, some accessories were installed before the mast was erected and some after. Figure 19 shows the tower in place.

5. MAIN MAST AND BLADE INSTALLATION

The last, most difficult, and critical procedure was the raising of the main mast and blade set into the vertical position above the tower. First, while the main mast rests on the ground, the two blades, upper mast bearing mount, lightning protection equipment, guy cables, and anemometer were attached as shown in Figure 20. Next, the entire mast assembly was raised such that the lower mast drive shaft coupled through a hinged knuckle to the upper tower bearing. A winch or "come-along" was then attached to one guy cable which passed over a gin pole. With personnel guiding the mast using the remaining two guy cables, the assembly was winched to the vertical position. Finally, the mast was jacked upward from the tower top, the hinged knuckle was removed and the mast drive shaft lowered through the upper tower bearing. The drive train flexible coupling inside the tower and the disk brake were then installed and the three upper guy cables secured. Pending final adjustments, and any remaining accessory installation, the turbine

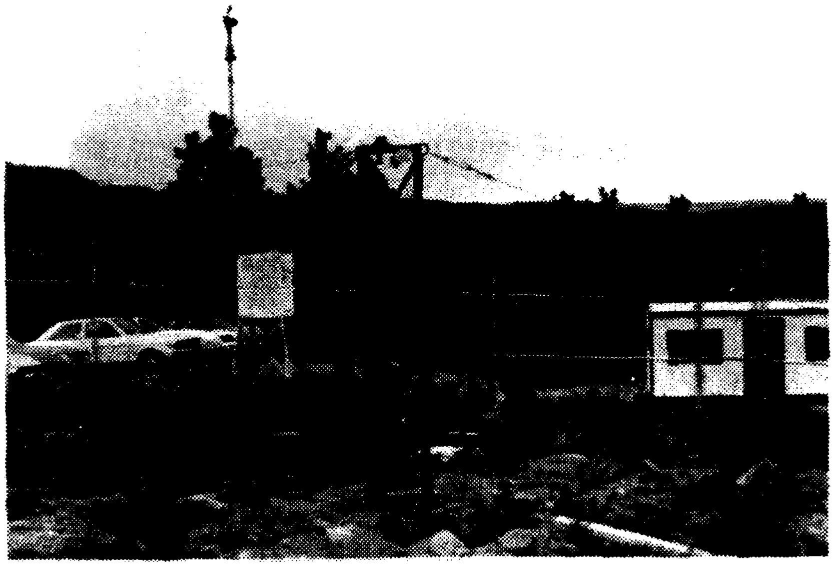

Figure 19. VAWT Tower

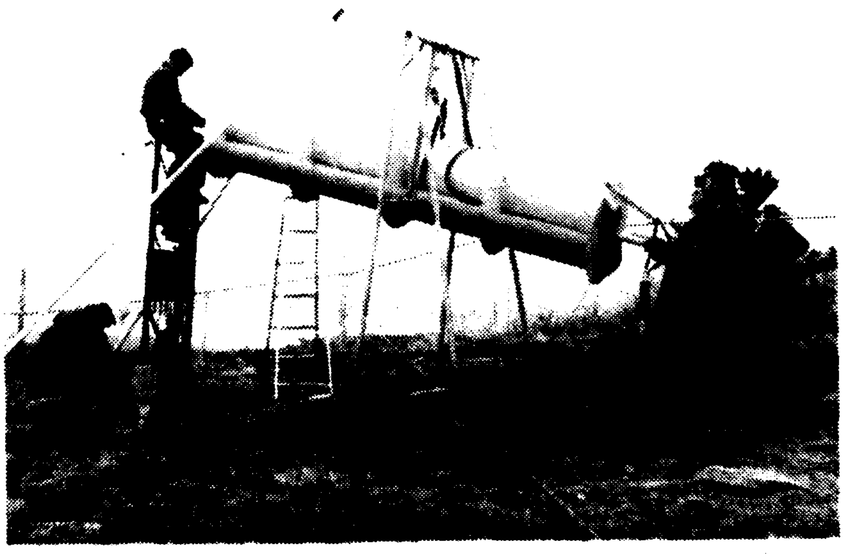

Figure 20. Main Mast Installation

installation was then complete. The turbine was in operation by mid-afternoon of the third day.

SECTION V

CONTROL SYSTEM

1. GENERAL BACKGROUND

An important goal of this project is the determination of an optimum control scheme for a variable speed VAWT. While many parameters necessary to determine this algorithm can be analytically calculated, others must be found through controlled field testing. In addition, optimum control must surely be verified and this can only be satisfactorily demonstrated in an environment of controlled field experimentation.

While the general control idea was known, the specifics of VAWT control through commanded changes in alternator field to optimize power output were not. Development of this algorithm can be done through hardware changes or with software manipulation using a microprocessor. Not only does a microprocessor permit rapid changes and flexibility but also a means of data storage and analysis. Therefore, the decision to base the control and data acquisition functions in a microprocessor occurred early in the life of this project. Since funding levels were insufficient to allow purchase of commercially available equipment, in-house development of software and hardware was completed.

2. HARDWARE

The data acquisition and control system hardware centers around a microprocessor based minicomputer. Two 8080 microprocessors, one the master and the other the slave, perform controlling/data gathering and data transferring functions, respectively. Software programming is done on the USAFA main frame computer and then transferred to EPROMs (Erasable Programmable Read Only Memory). These EPROMs are then installed in the minicomputer at the VAWT test site. Some limited software changes can be made through the terminal on-site but these are normally trouble-shooting functions.

Figure 21 shows a block diagram of the USAFA VAWT software development system with 8080 based microprocessor. The processor handles all input, output, control decisions, and data analysis under a general software operating system. Due to the real time control function and data storage requirements, the operating system is divided into control and analysis modes.

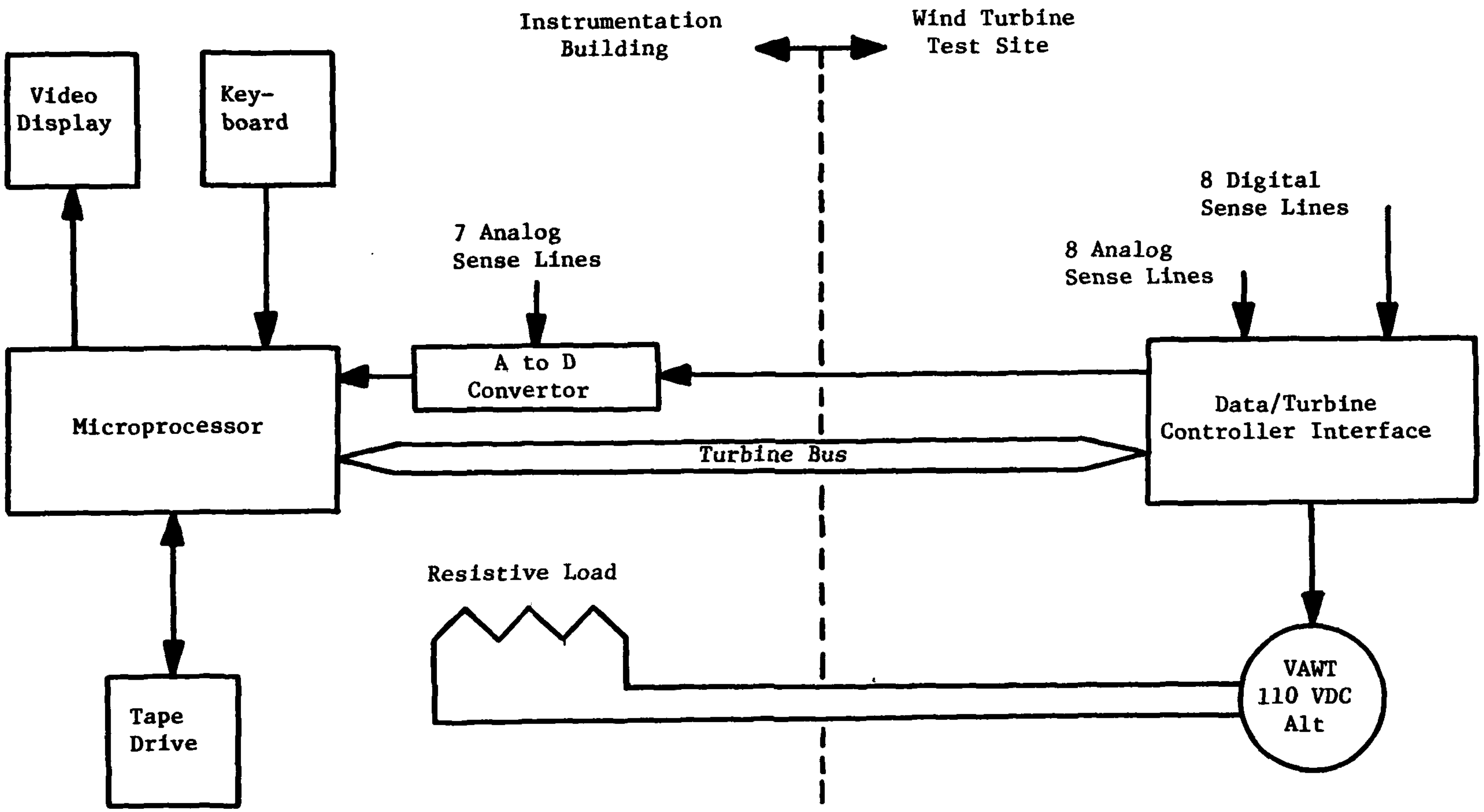

Figure 21. Software Development System

When in the control mode, optimum operating conditions are calculated and appropriate alternator field current modulation commanded. Sensors are then scanned, their values stored and a current status is displayed. In the analysis mode, data can be recalled from tape storage and recorded manually if desired. More frequently, recorded data tapes are transferred to a tape reader connected to an HP9830 desktop computer having resident data analysis software.

Data gathering for the VAWT is accomplished by electronics external to the minicomputer. An analog-to-digital board adjacent to the computer converts analog sensor readings to digital form. Sensor types and locations are shown in Table 4.

TABLE 4. SENSOR LOCATION

Sensor	Location
Barometric Pressure	Instrumentation Building
Wind Direction	Main Blade Centered Tower, 9.1 m North of VAWT
Wind Velocity 1	Main Blade Centered Tower, 9.1 m North of VAWT
Wind Velocity 2	1.2 m Above the Main Blades
RPM	Alternator Main Shaft
Brake Position	Brake Actuator
Vibration Sensor	Tower Top
Alternator Voltage	Resistor Bank, Outside Instrumentation Building
Temperature	Exterior to Instrumentation Building

3. SOFTWARE

The control software is resident in the minicomputer. Major control algorithm changes are accomplished through reprogramming of the EPROMs. Certain other control parameters are specified by direct input through the computer terminal keyboard and are displayed on the terminal screen (CRT). The CRT changeable parameters are listed and described in Table 5. The ability to alter these key parameters through the CRT during testing provides the flexibility necessary to "tune" the VAWT as a step toward finding the optimum control scheme for this variable speed VAWT.

TABLE 5. CRT CHANGEABLE PARAMETERS

Parameter	Effect
T	Commands constant tip speed ratio*
C	Commands cycle time through the control algorithm
D	Decrements or increments the alternator field by this amount at each cycle through the control program
P	Commands rpm at which controls switch from variable speed (constant tip speed ratio) to constant rpm operation
M	Specifies maximum rpm, above which VAWT is commanded to stop
U	Specifies maximum wind velocity above which VAWT is commanded to stop

The control program is shown as a block diagram in Figure 22. Initial entry to the algorithm begins when the operator selects the RUN mode at the CRT keyboard. If all conditions for starting are met, VAWT status is changed from STOP thru READY to RUN. Cycling through the algorithm then begins at a rate commanded by the operator. A STOP command from either the control program or operator actuates the braking system and results in VAWT shutdown. Return to the RUN mode after a braking sequence can only be done by the operator reintroducing the RUN command. It is anticipated that eventually all control functions may be moved to the VAWT tower once the optimum control algorithm is established. In such case, operation would be completely automatic to include restarts following braking. The only exception would be braking initiated by the tripping of the vibration sensor indicating a possible mechanical problem which would have to be corrected prior to restarting.

*Tip-speed ratio = blade tip speed ÷ wind speed.

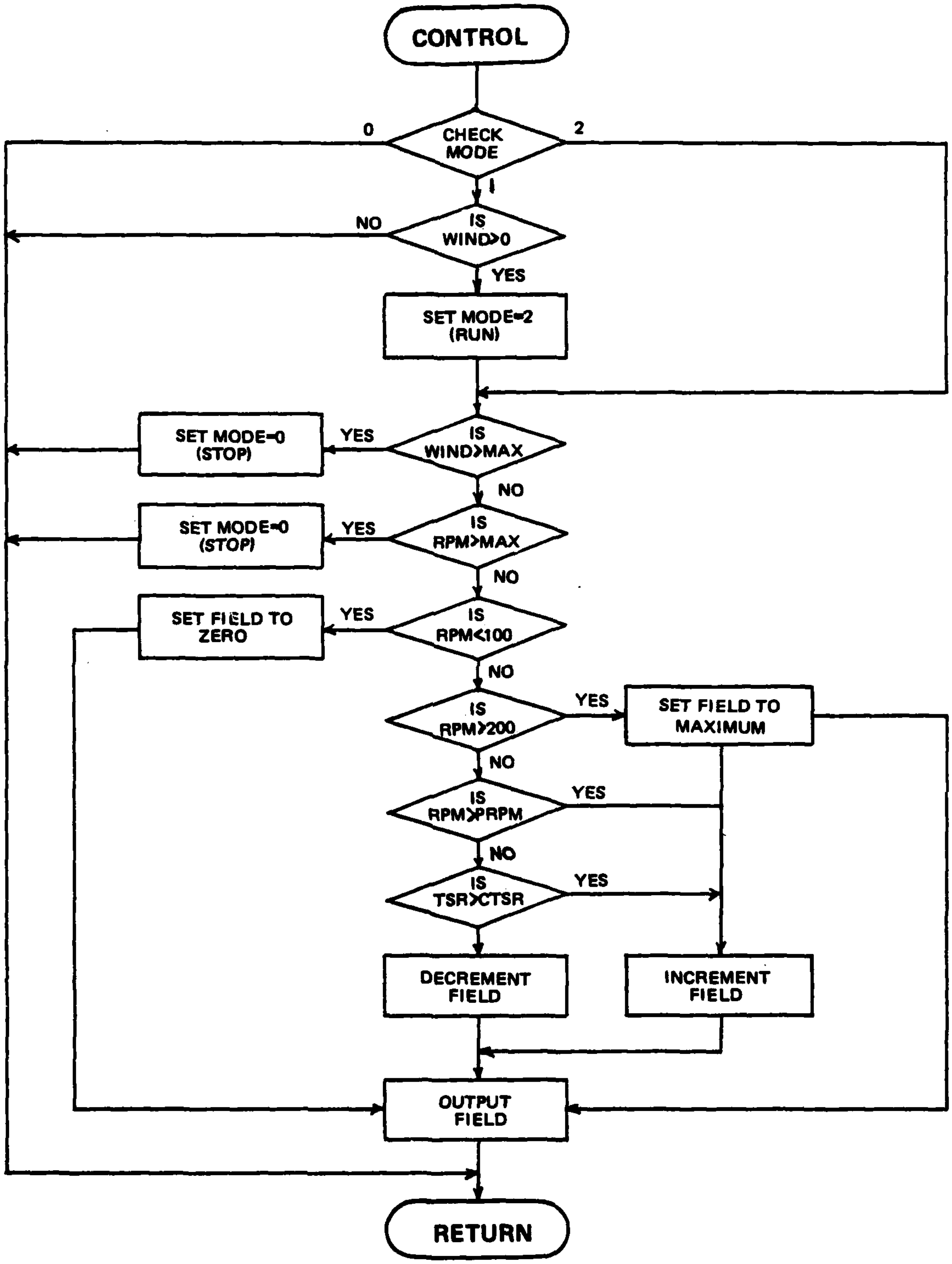

Figure 22. Control Program

SECTION VI

TURBINE PERFORMANCE

1. PREDICTED PERFORMANCE

The turbine is designed to operate within limits such that it can always be controlled by field current commands to the alternator and can be stopped by either the disk brake or the alternator acting independently. The brake may be adjusted to produce a maximum braking torque of 81 N·m (60 ft-lb). Alternator braking torque available through application of full field current was calculated from preliminary torque measurements made in the laboratory. The total torque produced by the turbine was predicted from wind tunnel data published by Sandia Laboratories (Reference 16). The results of these preliminary calculations are shown in Figure 23, in which torque is plotted versus wind speed for various turbine tip speed ratios.

Maximum turbine torque is produced at a tip speed ratio of 5, and at this tip speed ratio, the maximum braking torque of the disk brake will be exceeded when the wind speed exceeds 11.2 m/s (25 mph). Thus, 11.2 m/s is the maximum operating wind speed for a tip speed ratio of 5. Similarly, the maximum operating wind speed for a tip speed ratio of 4 is 15.2 m/s (34 mph). At a tip speed ratio and operating rpm of zero (VAWT parked), the maximum allowable wind speed is 22.4 m/s (50 mph). In winds exceeding 22.4 m/s the turbine must be tied down or it will turn thru the disk brake.

In Figure 24, the alternator braking torque available at various tip speed ratios is illustrated along with the turbine torque produced. The alternator braking curves shown also include a 6.8 N·m (5 ft-lb) frictional drag. At a tip speed ratio of zero, representing the start up condition, the turbine torque exceeds the frictional drag when the wind speed exceeds 6.3 m/s (14 mph). It should be noted, however, that the turbine torque shown is an average value, and at some orientations of the Savonius buckets, the actual static torque produced may be as much as 35 percent less than above. Thus, a wind gust to as high as 8.1 m/s (18 mph) may be required to start the turbine. Once the turbine has started and accelerated to a tip speed ratio of greater than 4, continued operation should be possible in wind speeds as low as 4.5 m/s (10 mph).

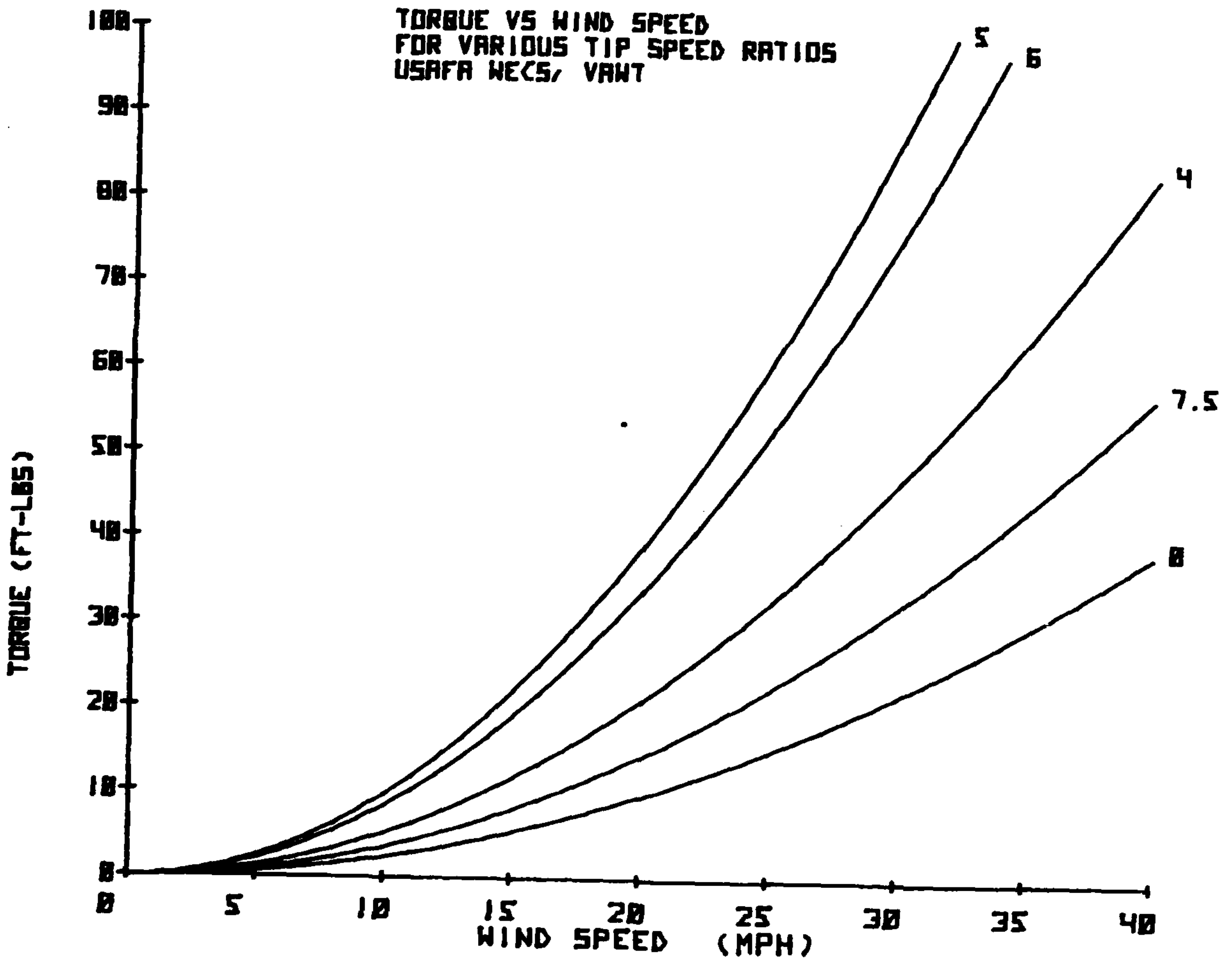

Figure 23. Predicted Torque at Different Tip Speed Ratios

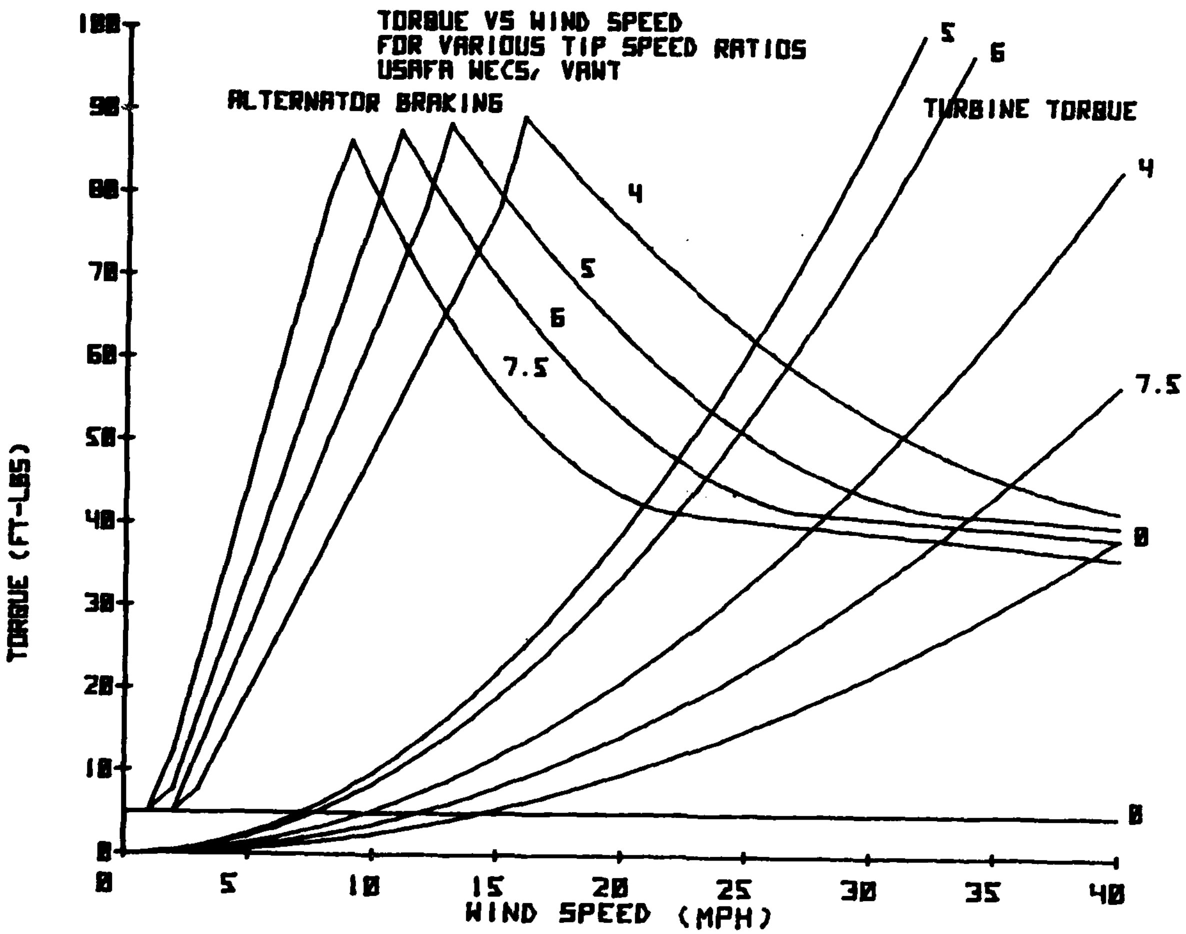

Figure 24. Alternator Control Braking and Predicted Torque at Different Tip Speed Ratios

At wind speeds greater than 10.3 m/s (23 mph), the turbine is capable of producing more torque than the alternator. To ensure that the alternator will have some excess braking torque with which to maintain control of the turbine rpm, the tip speed ratio must be decreased as the wind speed approaches 10.3 m/s (23 mph). As the wind speed approaches 17.9 m/s (40 mph), the torque produced approaches the maximum alternator braking torque available regardless of operating rpm. Thus, the maximum predicted operating wind speed is 17.9 m/s.

Figure 25 shows how the turbine torque produced varies with rpm for various wind speeds. In a 10.3 m/s wind, a commanded tip speed ratio of 5 would result in operation at 225 rpm. This condition represents the maximum torque the turbine can produce at that wind speed and the limit of alternator control. If a constant rpm is maintained as the wind speed increases above 10.3 m/s, the tip speed ratio, and thus the turbine torque produced, decreases while the alternator torque available remains the same. Thus, under the control algorithm of constant tip speed ratio operation followed by constant rpm operation as wind speed increases to a maximum of 17.9 m/s, excess alternator braking torque will always be available.

Figure 26 shows the turbine power produced as a function of wind speed. A constant tip speed ratio of 6 (for maximum power output) is maintained in wind speeds less than 10.3 m/s. In a 10.3 m/s wind and at an rpm of 225, the alternator will produce about 1200 watts. As the wind speed increases beyond 10.3 m/s, the power output will decrease to a minimum of about 1000 watts in a 14.8 m/s (33 mph) wind. In winds greater than 17.9 m/s, the turbine would be shut down.

2. TEST RESULTS

Predicted braking curves are illustrated in Figures 27, 28, and 29. Figure 27 shows the braking time predicted for the disk brake only from 250 rpm with various wind speeds. The braking torque produced is periodically checked and the curves shown are based on a torque of 81 N·m (60 ft-lb). Laboratory testing has shown that brake fade should not be a factor as long as the braking time is less than 60 seconds. Figure 28 shows the predicted braking for the alternator only, and Figure 29 shows the combined braking predicted for both the alternator and the disk brake operating together.

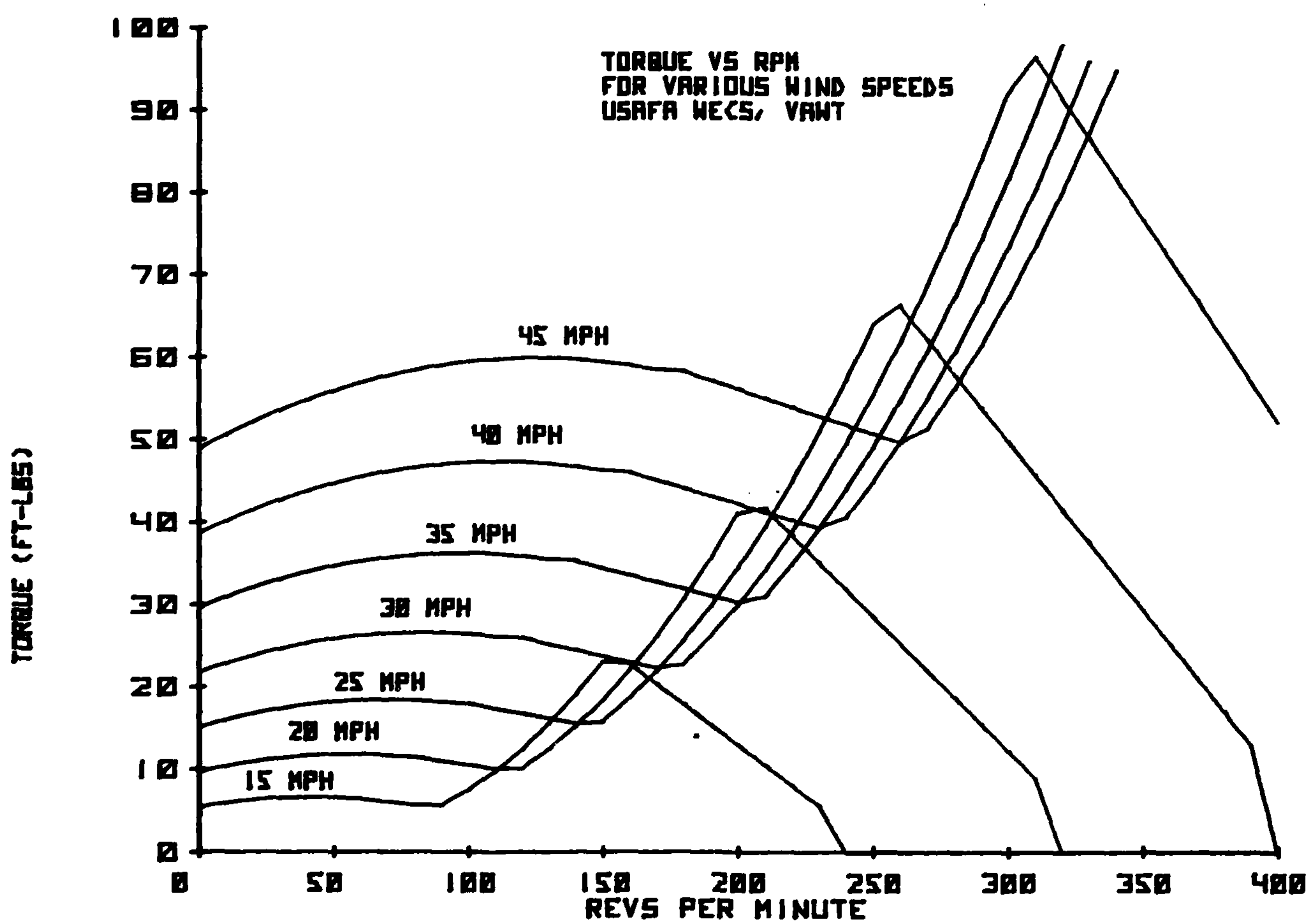

Figure 25. Predicted Torque at Different Wind Speeds

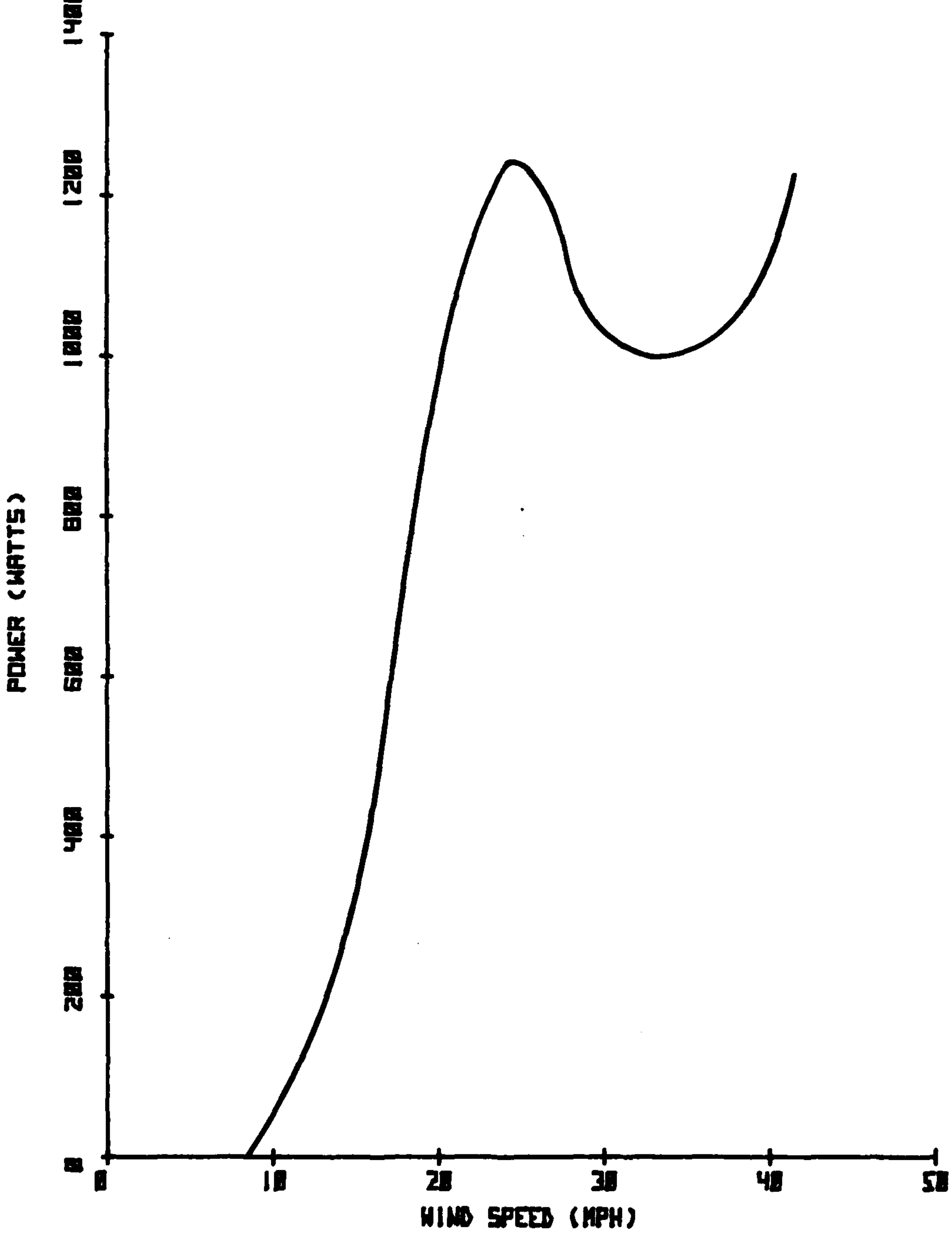

Figure 26. Predicted Power Output

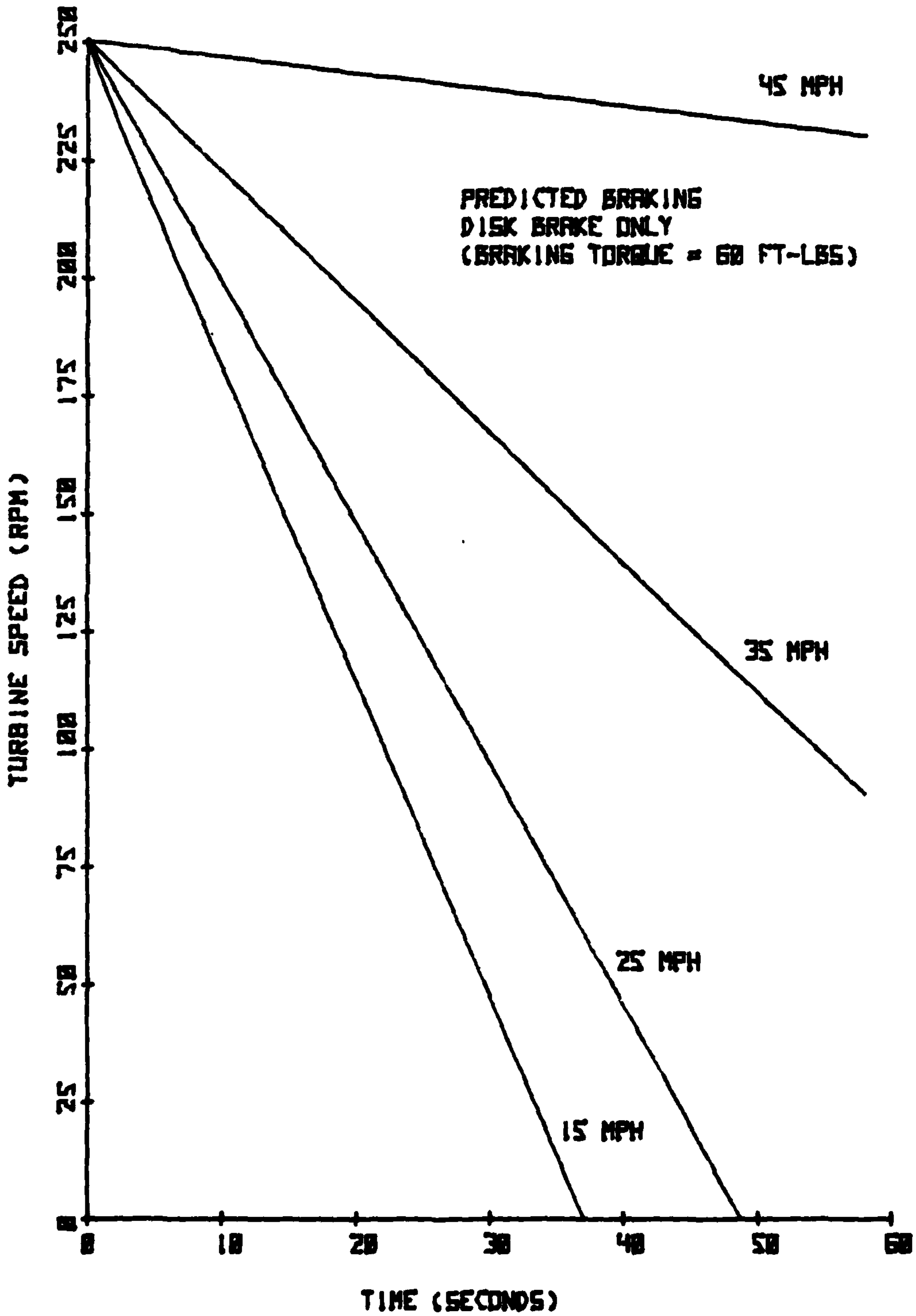

Figure 27. Predicted Braking - Disk Brake Only

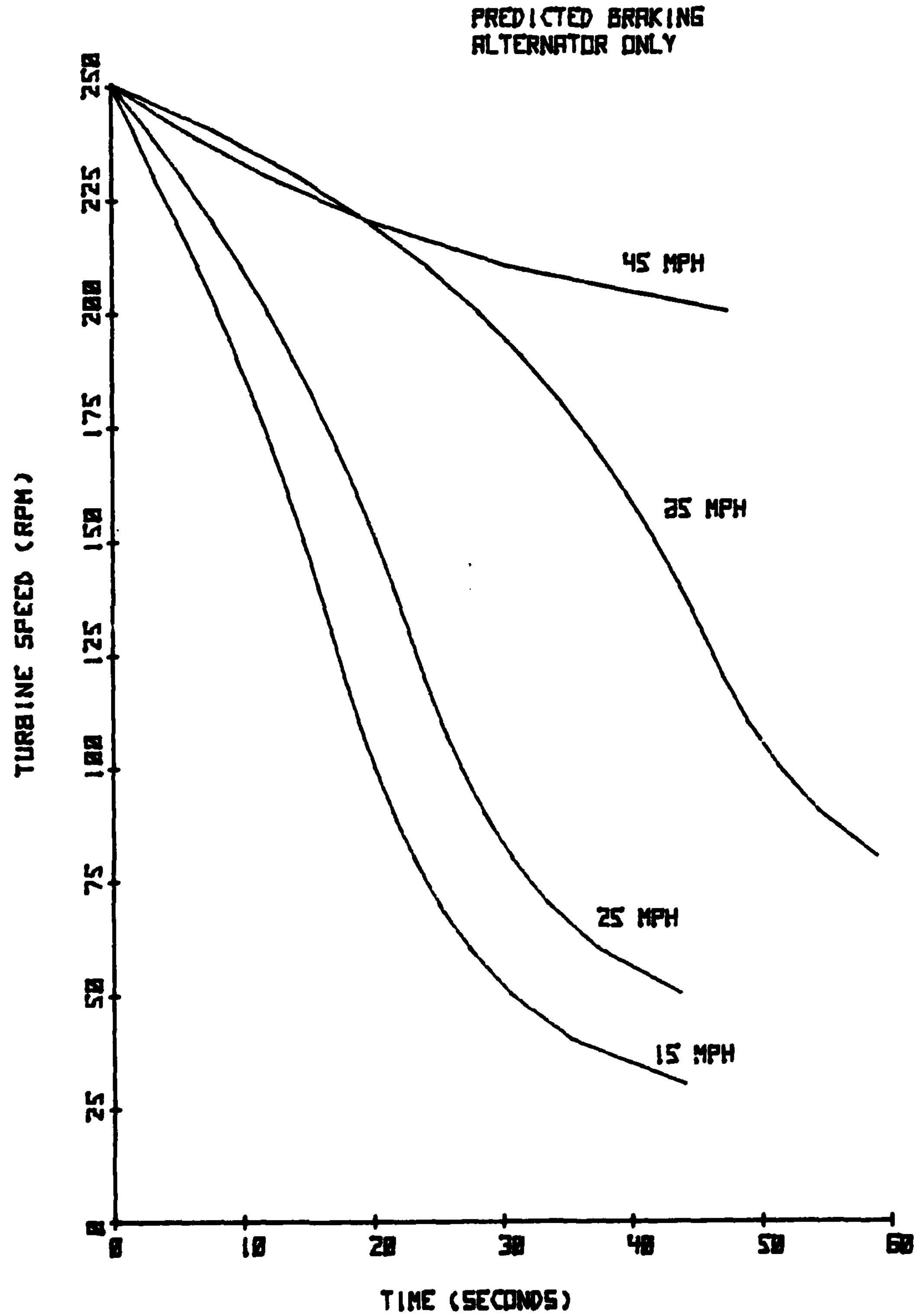

Figure 28. Predicted Braking - Alternator Only

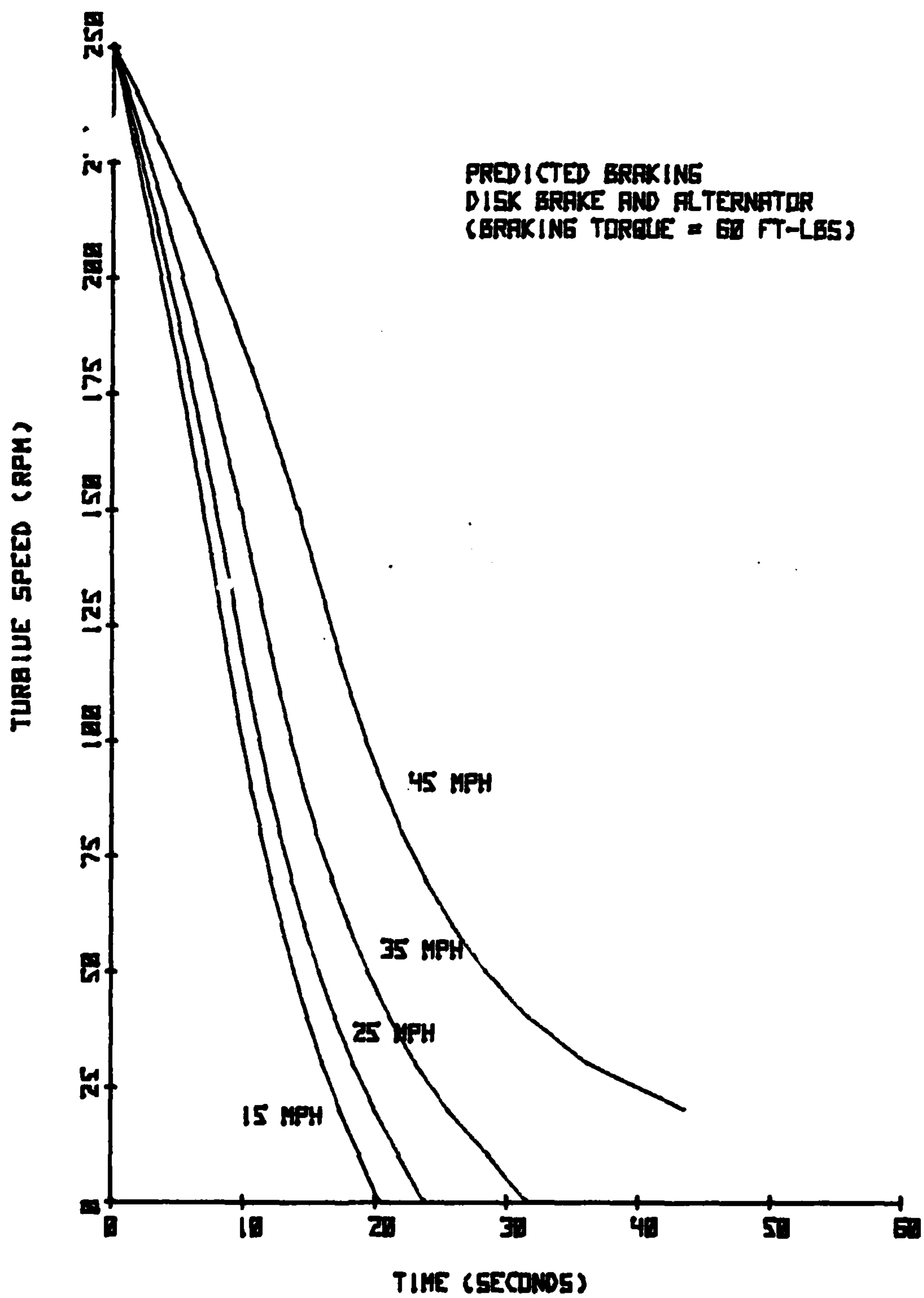

Figure 29. Predicted Braking - Both Disk Brake and Alternator

Preliminary testing was conducted to verify the predicted braking curves. Figure 30 shows the results of braking data taken with the disk brake only in a 3.13 m/s (7 mph) wind. The solid line shows the predicted values for the actual braking torque of 76 N·m (56 ft-lb). The turbine was driven to 120 rpm with an electric motor prior to braking. Data was recorded only down to 60 rpm and the rpm was rounded off to the nearest 10 by the microprocessor data acquistion system. Figure 31 shows similar data taken in a 3.13 m/s (7 mph) wind with the alternator only. Figure 32 shows a braking test in a 1.34 m/s (3 mph) wind using both the disk brake and the alternator. Data was recorded down to zero rpm. The preliminary braking tests showed that the disk brake performed slightly better than predicted and the alternator braking was about as predicted. Since the wind was light during these tests, very little torque was produced by the turbine. This is reflected in the predicted braking curves; however, these tests give little indication about how accurate the predicted braking curves will be in stronger winds when the torque produced by the turbine becomes more important. The results of two additional braking tests conducted in stronger winds are shown in Figure 33. During these tests, turbine speed was recorded to the nearest rpm. While the shapes of the curves appear to differ slightly from predicted (as shown by the solid lines) the overall braking performance came very close to the predicted performance. At this point, it was concluded that the performance predictions were sufficiently accurate to permit safe operation of the turbine within the operating limits specified earlier.

Data from a typical starting sequence is shown in Figure 34. The wind speed varied from about 8.5 to 13 m/s (19 to 29 mph) and the turbine reached an operating speed of 100 rpm in about 30 seconds. At 10 seconds, a large drop in rpm without an accompanying drop in wind speed is apparent. This is typical of the difficulties expected in comparing turbine performance with wind speed taken from a single fixed location.

Figure 35 shows typical turbine operation during early testing. Wind speed and turbine speed are shown as a function of time while the controller attempted to maintain a constant speed of 110 rpm. During this test, the computer was programmed to increase the alternator field at a constant rate when the turbine speed was greater than 110 rpm and to decrease the field at a constant rate when the speed was less than 110 rpm. In this case, the

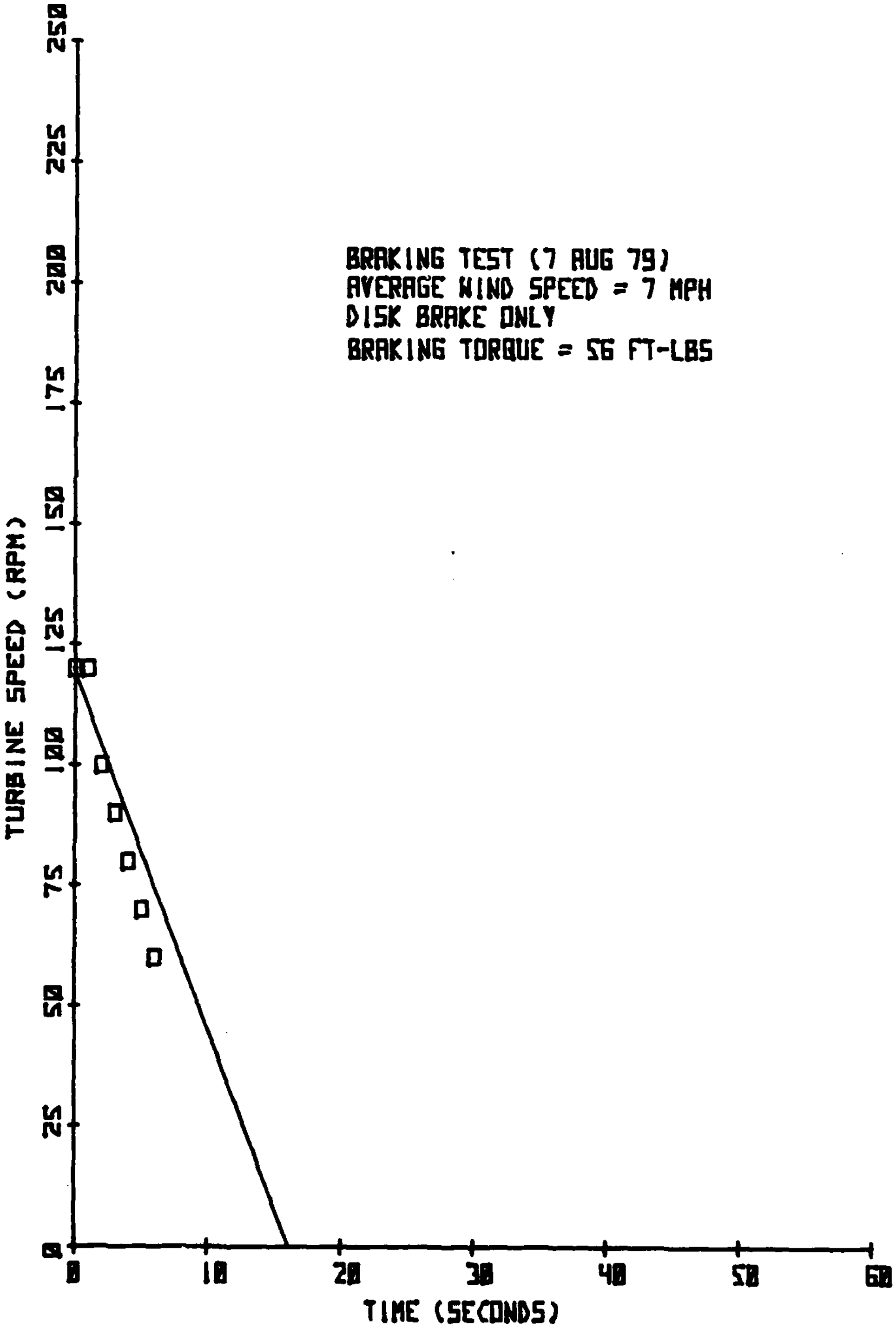

Figure 30. Braking Test - Disk Brake Only

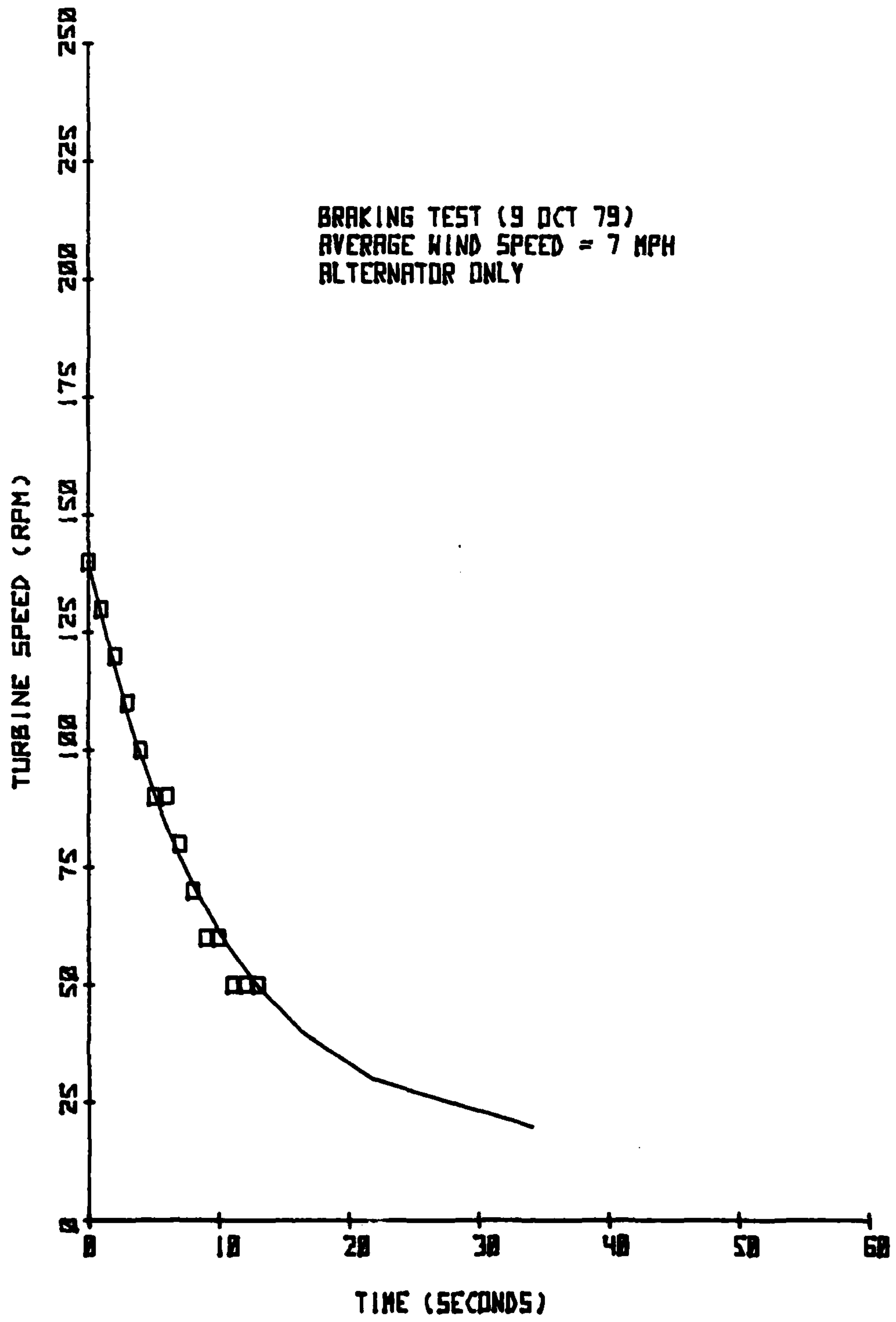

Figure 31. Braking Test - Alternator Only

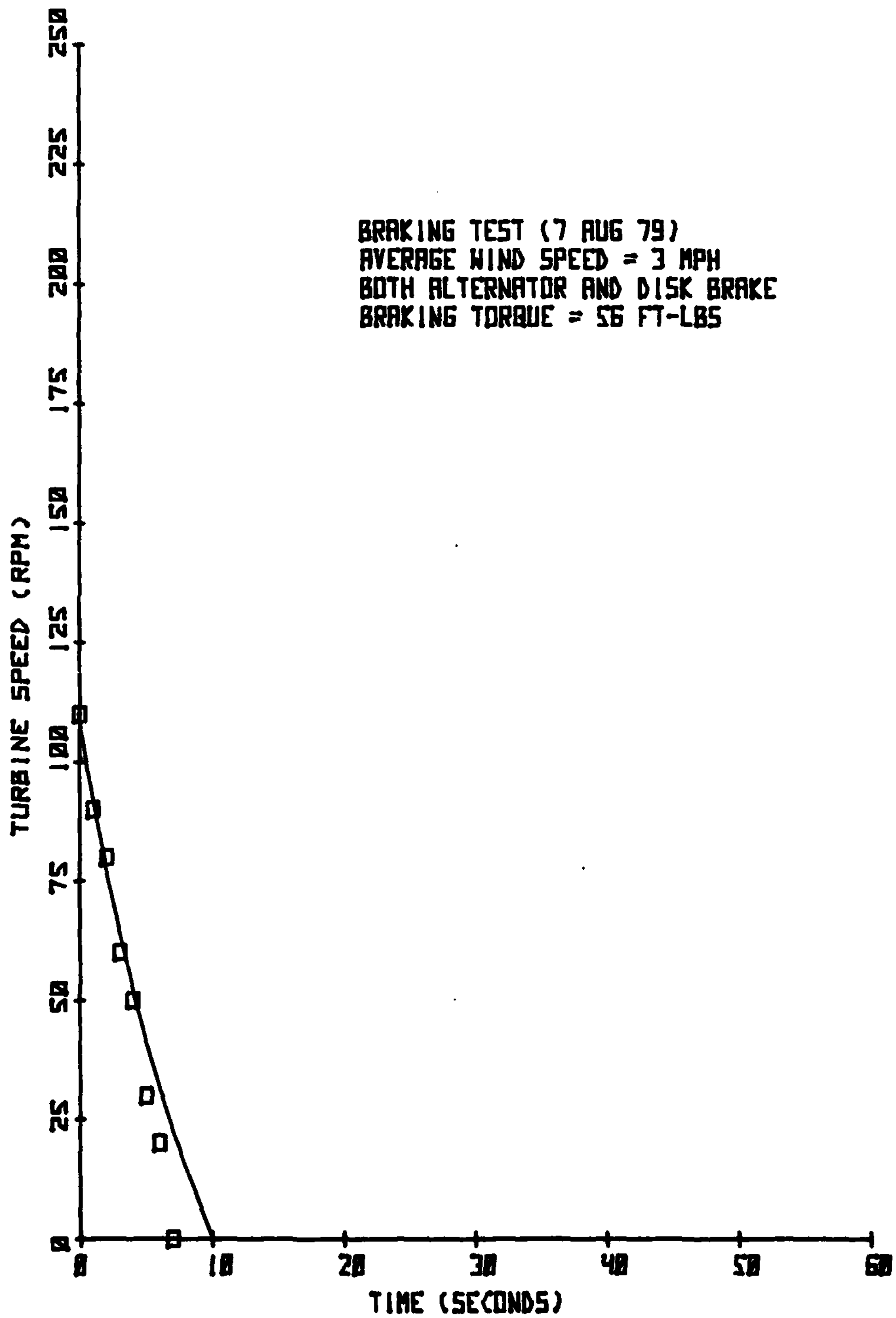

Figure 32. Braking Test - Both Disk Brake and Alternator

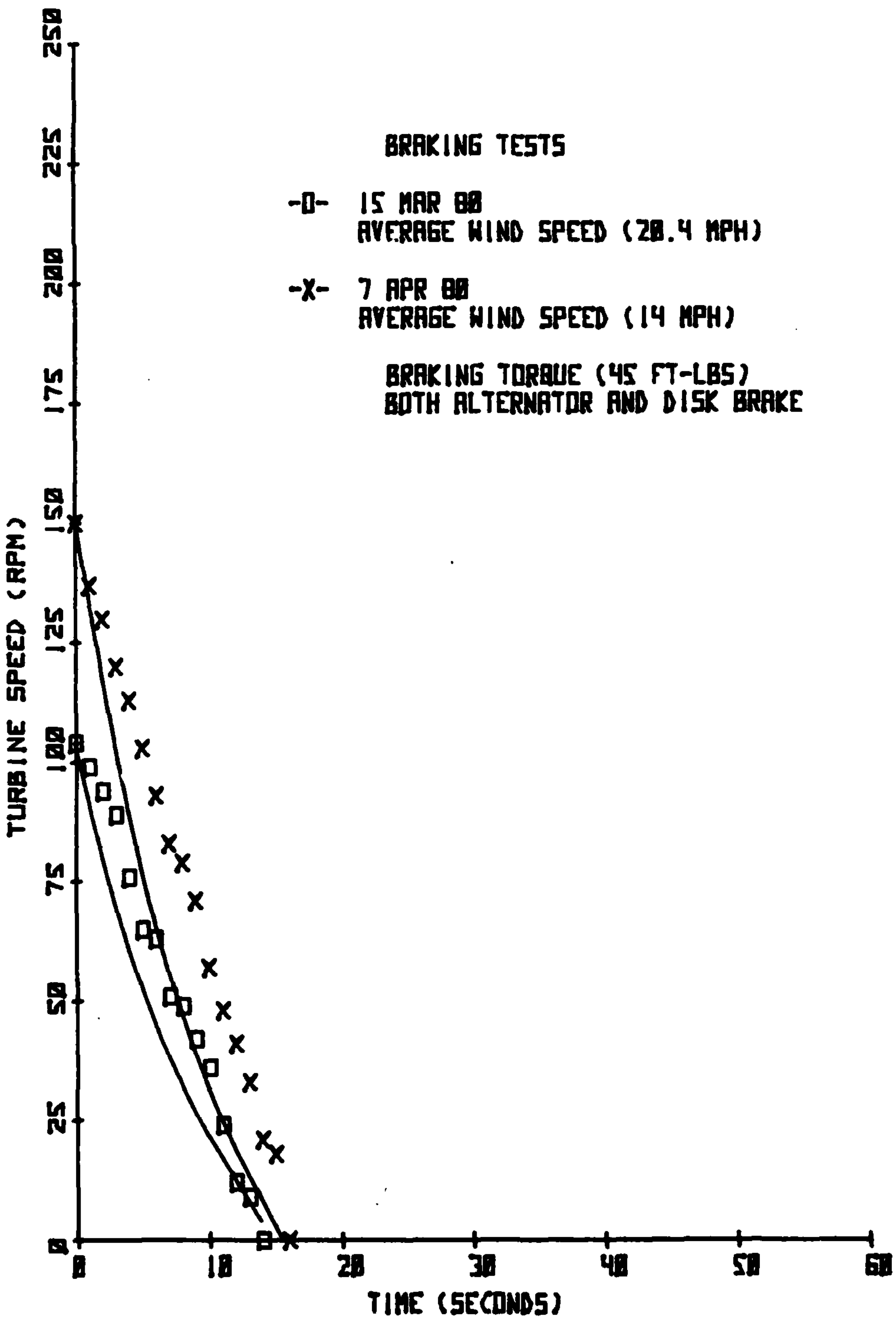

Figure 33. Braking Test - Both Disk Brake and Alternator

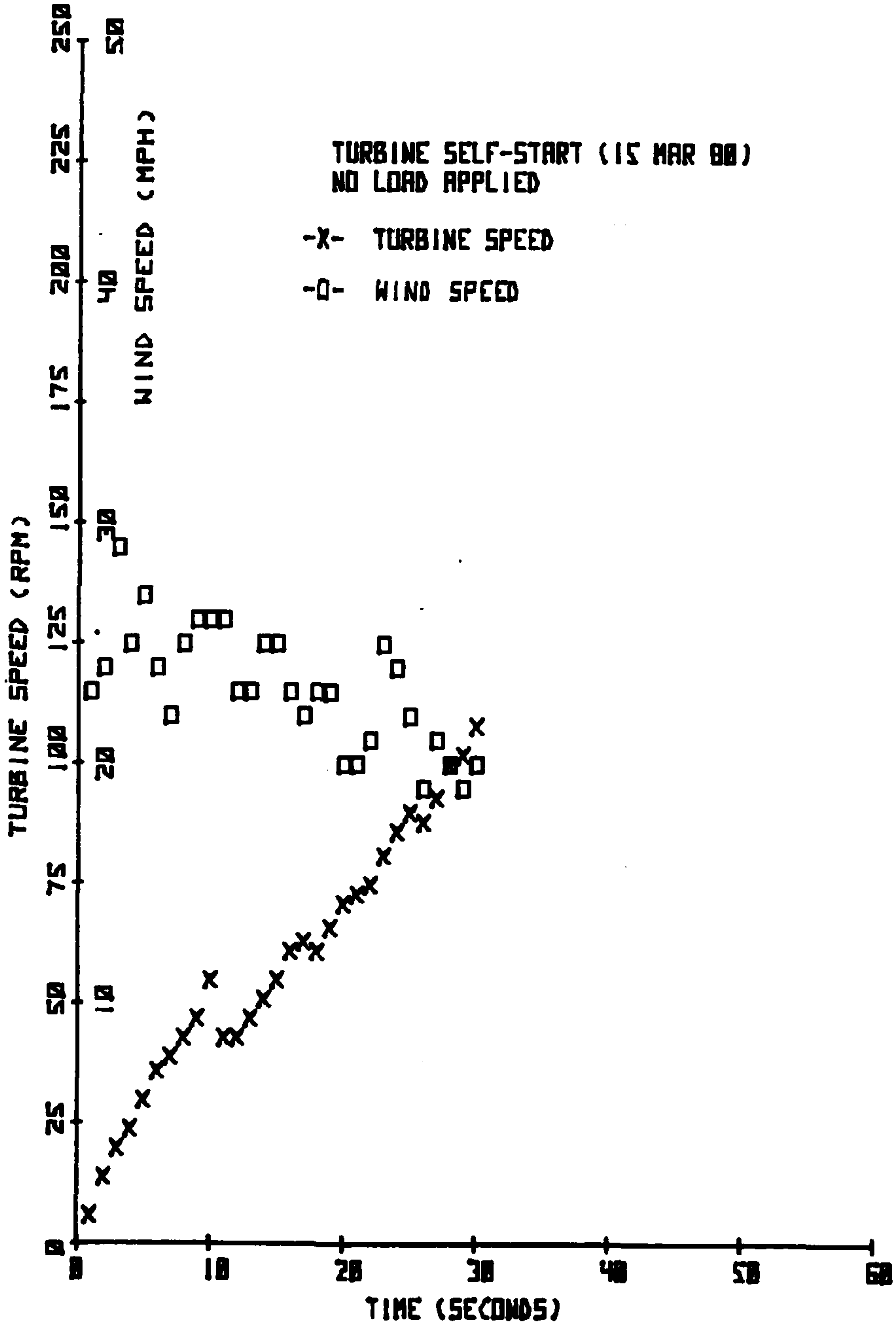

Figure 34. Starting Performance

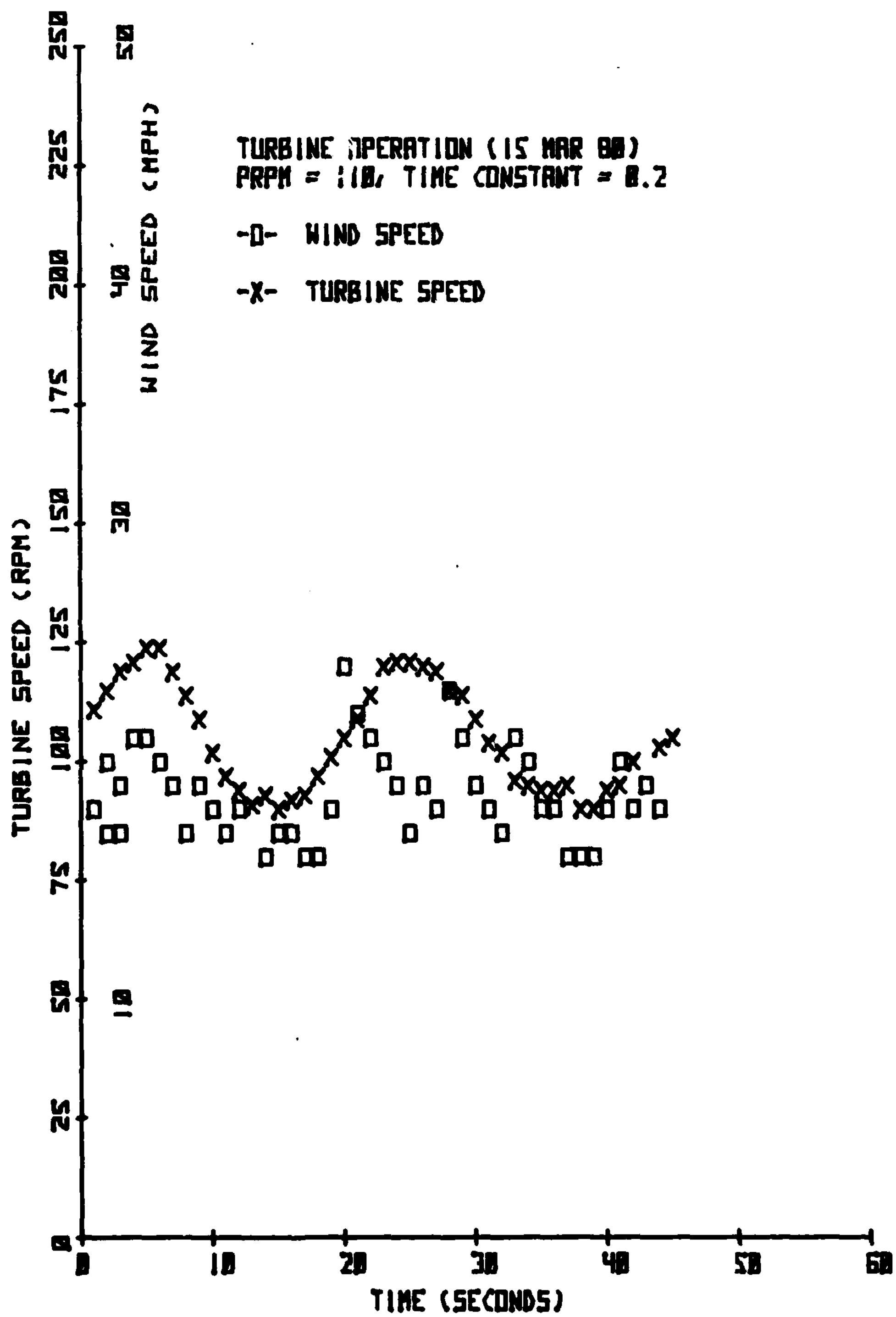

Figure 35. Controller Performance - Constant rpm

rate at which the alternator field was changed was set at the maximum available. In other tests, decreasing the rate at which the field was changed increased the magnitude of the deviations in turbine speed.

The average turbine tip speed ratio during the test shown in Figure 35 was 2.8. Turbine speed during early testing was intentionally kept low to increase the margin of safety in case some malfunction should occur. At this tip speed ratio, very little torque is produced by the Darrieus blades and the total output is nearly the same as expected from the Savonius starting turbine alone.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

1. CONCLUSIONS

One objective of the USAF Academy Wind Energy Conversion System Project; to design, fabricate and test a small vertical axis wind turbine; has in large part been completed. VAWT design and fabrication is finished and field testing is underway. Testing to date has shown that the design approach of Section I.5 appears to be valid.

Testing delays incurred since VAWT installation are due to two factors. The test site average wind speed is 2.24 m/s (5 mph) which severely limits available testing periods. This site was chosen early in the project based on its convenient location and the availability of commercial power. Continuing hardware problems in the microprocessor data acquisition and control system have limited field testing even further. This system was designed and built in-house due to the lack of funds for a commercial unit. Today, this problem would not exist since suitable low-cost commercial systems are readily available. In spite of these difficulties, the potential for turbine control using commanded alternator field modulation has been clearly demonstrated.

2. RECOMMENDATIONS

Future USAF wind turbine test and field evaluation programs should be conducted at sites chosen primarily because of a suitable known wind resource and not strictly for convenience. Since the VAWT is installed and operating, further testing should be accomplished to validate the design approach and fully meet the project objective. The search for an optimum control algorithm should be completed. In addition, the contribution of aerodynamic starting should be established.

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APPENDIX A

PRELIMINARY DESIGN FAILURE ANALYSIS

1. PRELIMINARY DESIGN

The original wind turbine was designed and built around a locally purchased mast and blade assembly. A self-starting capability was achieved by mounting Savonius rotors on the mast.

Optimum starting performance was sought by using rotors each having a two-bucket configuration and orientation 90 degrees to one another as shown in Figure A-1. The rotors were located near the ends of the mast to minimize the aerodynamic interference with the main Darrieus blades. The Savonius starting rotors were designed to produce a starting torque of 5.8 N·m (4.3 ft-lb) at zero rpm decreasing to 4.2 N·m (3.1 ft-lb) at 100 rpm in a 5.8 m/s (13 mph) wind. At 100 rpm, the Darrieus turbine would be fully self-sustaining and acceleration would continue to an operating tip speed ratio of 6 at which point the starting torque would be approximately zero. To meet these design requirements, each Savonius rotor was made 90 cm (36 in) long by 109 cm (43 in) in diameter with a gap-to-width ratio of 0.24. The mast passes through the center of the Savonius and reduced the effective gap-to-width ratio to 0.17.

2. FAILURE DESCRIPTION

After the turbine was assembled in the field for testing, it was noted that the mast had approximately a 50 mm (0.2 in) eccentricity; however, the decision was made to conduct preliminary testing prior to straightening the mast. The computed static buckling load was 13,700 lb which provided a safety factor of 14.

Preliminary alternator braking tests were conducted on 8 November 1978 with wind speeds to 8.9 m/s (20 mph) with the disk brake locked open. Alternator braking appeared normal with the alternator producing a peak output of 1300 watts and slowing the turbine to about 25 rpm. On 22 November 1978, additional braking tests were conducted in winds to 8.5 m/s (19 mph). A strip chart recorder was used to provide a temporary rpm readout. When alternator braking was commanded, the microprocessor failed to apply a field current to the alternator and braking did not occur. At about 265 rpm,

mast vibrations were observed and the strip chart recorder was turned off. The vibrational amplitude rapidly increased and, within 6 seconds, the mast buckled in the center and the turbine collapsed.

The failure was relatively tame with no flying parts and limited damage. The Darrieus blades were severely deformed but remained intact. The mast was bent in the center at an angle of about 110 degrees. The support tower was undamaged and remained standing. Apparently, most of the rotational energy was absorbed when the Darrieus blades struck the lightning arrestor grounding cables. Figure A-2 shows the extent of the damage.

3. FAILURE ANALYSIS

Analysis of the failure indicated that the addition of the Savonius rotors to the mast reduced the main shaft critical speed from 600 to 330 rpm. This reduction in the critical speed combined with the failure of the microprocessor to command alternator braking were the primary causes of the failure. Contributing factors included the mast eccentricity and possible dynamic coupling with the guy cables.

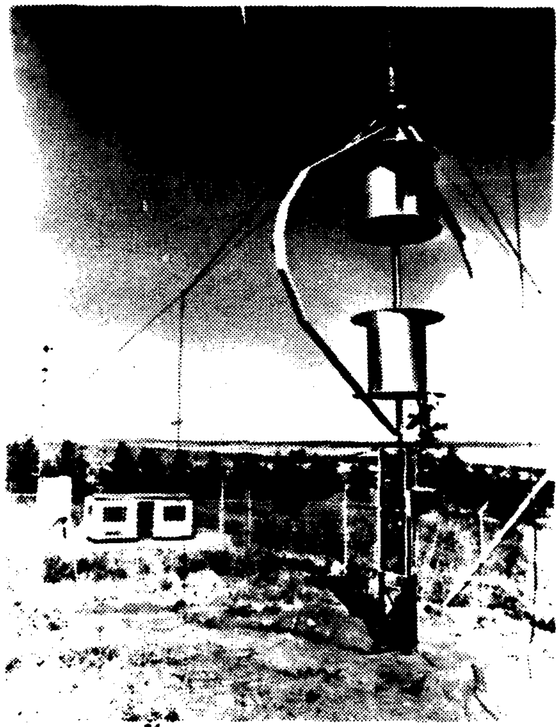

Figure A-1. Preliminary VAWT Configuration

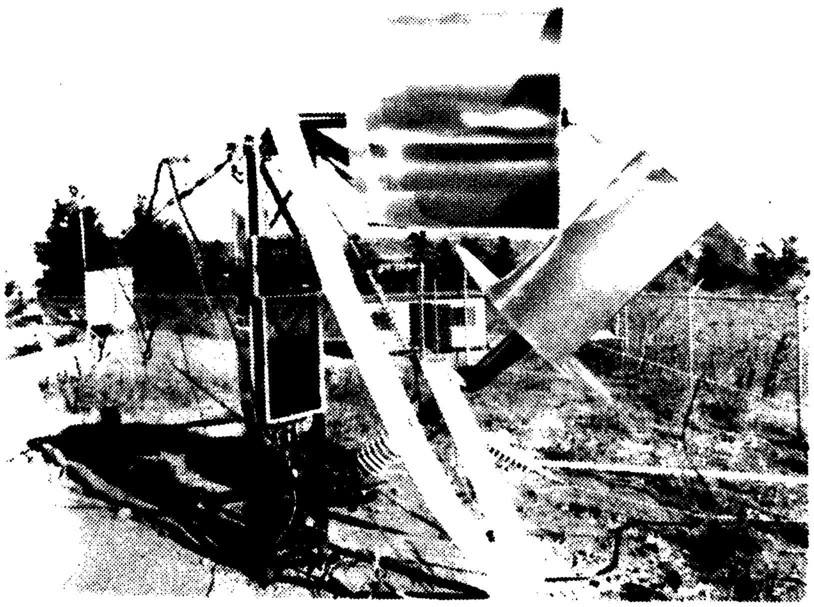

Figure A-2. VAWT Main Shaft Failure